masonry council of canada

GUIDE TO ENERGY EFFICIENCY IN MASONRY AND CONCRETE BUILDINGS

April 1982

Further copies of this Guide may be obtained from the:
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Foreword

Most Canadians recognize that today's energy costs are high and they accept that future costs will be higher. They see also rapid changes taking place in many areas of technology, in an effort to conserve energy and to save money. One such area of change is in the building construction industry. Some energy problems in new buildings could be avoided if designers and builders developed a better understanding of the technological principles which effect overall building behaviour.

All construction elements in new energy efficient buildings must be properly coordinated, if a functionally sound and cost-effective building is to result. The effect of novel design features on the new, completed structures must be understood.

Several Canadian publications are available to assist in the design of energy-conserving buildings. None of these publications, however, specifically addresses the design of the larger masonry and concrete structures.

This Guide has been prepared to fill that need. Basic information is provided permitting the design of energy-efficient buildings which will function well, in all traditional respects, and provide for optimum, long-term cost-effectiveness, in the Canadian environment. Since new buildings are in the best interests of all, the preparation of this publication has been jointly funded by the Masonry Council of Canada, Canada Mortgage and Housing Corporation and the National Research Council of Canada.

It sets forth the basic principles which may be used when designing energy efficient masonry and concrete buildings. It explains the inter-relationships between the features necessary to achieve a high degree of energy efficiency, and those features which have been traditionally recognized as essential to good building practice. It provides guidance on detailing practices and assembly concepts and discusses the mass related benefits which can be derived from the use of masonry and concrete in construction. A means is then developed of assessing the overall cost-effectiveness of these various aspects of design.

The portion of this Guide that deals with the benefits of mass, in energy conservation, reflects the results of numerous reports on the performance of massive buildings, as well as a recent report, by the consultants for CMHC. Based on the new work, on-going research is underway or being planned in this area, to further improve the understanding of the effect of mass, in energy consumption. This will allow more ready calculation of those mass effects, during the design process.

The timely appearance of this Guide will be a valuable aid to those now responsible for the design and construction of a new generation of masonry and concrete buildings; which must operate efficiently in the Canadian climate.

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CANADA MORTGAGE AND HOUSING
CORPORATION

Note: This publication is based on the facts and authorities stated herein. It is intended for the use of professional personnel competent to evaluate the significance and limitations of the information provided and who will accept responsibility for the application of the material. The Masonry Council of Canada disclaims any and all responsibility for application of the stated principles to specific buildings or for the accuracy of any of the sources.

Preface and Acknowledgements

This publication represents the first major project undertaken by the Masonry Council of Canada, whose members are the:

- Canadian Masonry Contractors' Association
- Canadian Portland Cement Association
- Clay Brick Association of Canada
- International Union of Bricklayers and Allied Craftsmen
- Labourers International Union of North America
- National Concrete Producers' Association

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Illustrations appearing in the Guide were prepared by Robert Bordeau and Michael Coakeley, CMHC National Office Support Centre.

The Masonry Council wishes to thank all of those who participated in the preparation of this publication and hopes that the "Guide to Energy Efficiency in Masonry and Concrete Buildings" will prove to be a useful addition to existing Canadian literature in the field of energy conservation in buildings.

The Masonry Council of Canada
1982

Guide to the Use of Masonry and Concrete in Energy Efficient Buildings

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SECTION 1
INTRODUCTION AND SCOPE

1.1 Intent

This publication is intended to assist those involved in the design and construction of masonry and concrete buildings in meeting the challenge they now face — the challenge of making buildings more energy efficient without sacrificing serviceability and durability and without incurring unwarranted premiums in construction cost. This challenge is created by two factors — economics and building regulations.

The already high and continually increasing cost of energy dictates that building designers have a responsibility to their clients to give greater priority than in the past to energy efficiency. In general, making buildings more energy efficient is in the best interests of all those involved in the building process — designers, developers, owners, tenants, contractors **and** society as a whole.

As a reflection of society's interest in this area, governments at all levels are now taking steps to increase the regulation, in building codes, of factors which affect a building's energy efficiency. Except for residential buildings, these factors have traditionally been largely unregulated. This is changing rapidly as governments realize the negative effect which excessive energy consumption has on our economy and appreciate the major role which buildings of all types play in determining our national energy needs.

However it is in the former context of enlightened self-interest of building developers, owners and designers that this Guide has been developed. It is intended primarily to help them select and reach their own energy goals rather than being directed toward compliance with imposed regulations, although this is dealt with as well.

This Guide does not address the many long-recognized attributes of masonry and concrete materials that lead to their use in buildings —

- economy
- fire resistance
- rigidity
- sound separation
- design flexibility
- durability
- pleasing appearance
- etc.

Rather, it starts with the assumption that masonry and/or concrete construction has already been selected or is being considered, for the above reasons, and the next issue to be addressed is the energy efficiency of the building.

This Guide deals mainly with the relationship between energy consumption and the basic building fabric with emphasis on the outer building envelope. It is not intended to be a general guide to building design, nor does it deal in any detail with building mechanical system design. The Guide is therefore concerned with the following topics:

— methods of improving the thermal resistance and airtightness of the building envelope without increasing the risk of damage from rain penetration and interstitial condensation

— the role which building mass can play in reducing a building's consumption of energy for space heating and cooling and in improving the comfort of the occupants

— methods of assessing the cost effectiveness of energy conserving measures.

There are many publications available that deal with energy conservation in small residential buildings of wood frame construction. This Guide is intended to remedy the scarcity of information of this nature which is more generally applicable to a broader range of buildings and to masonry and concrete construction.

1.2 Types of Construction

This Guide addresses the following types of construction and various combinations thereof:

— concrete block masonry
— brick masonry
— brick veneer
— cast-in-place concrete
— precast concrete

It does not address masonry and concrete foundations since the principles involved are quite thoroughly dealt with in the publication "Builders' Guide to Energy Conservation in New Housing" published by the Housing and Urban Development Association of Canada.

1.3 Types of Buildings

The details and methods given in this Guide are generic in nature and suitable for use in most types of buildings in which the interior environment is controlled and this control is primarily directed toward the comfort of human occupants. Thus these details and methods may **not** be applicable in buildings such as ice rinks, swimming pools, non-enclosed buildings such as grandstands and parking garages, industrial buildings housing major heat producing processes such as smelters, industrial buildings housing corrosive atmospheres such as refineries, silos and grain elevators, cold storage buildings, and farm buildings.

1.4 Use of This Guide

This Guide has been written primarily from the point of view of those members of the building design team concerned with the building envelope — the architect and structural engineer. It is intended to lead these team members through a step-by-step process which can be followed iteratively to arrive at the highest level of energy efficiency of the building shell which is consistent with the economic criteria of the building developer or owner. It is expected that the Guide or parts of it will also be helpful to building developers and owners in articulating their economic criteria and in generally communicating with their design teams on the subject of energy efficiency of the building shell. It may also be helpful to others who must deal with the design team, such as building officials and materials suppliers, and to prospective members of the design team, namely architectural and engineering students.

The step by step process referred to above is as follows:

— First it is necessary to develop an understanding of how the building envelope functions, why it sometimes malfunctions and which characteristics of the building envelope affect its energy efficiency and to what degree. **Section 2, Basic Principles of Building Physics**, lays down the basic theoretical groundwork for the succeeding steps. **Section 3, The Effect of Building Mass**, addresses in greater detail a particular aspect of building physics of special significance in masonry and concrete buildings.

— Next it is necessary to review the available methods of making various types of building assemblies more energy efficient, the opportunities they provide and the limitations they impose. **Section 4, Insulating Building Assemblies**, outlines the **practical** factors which must be considered in improving the building envelope and provides a number of optional details which can be used in various circumstances to achieve improved performance with minimum risk of problems.

— When confronted with a wide choice of energy conserving options it is necessary to assess, in monetary terms, the saving which each can achieve. Due to the volatility of energy prices this Guide does not attempt to provide pre-calculated savings for different options; however, **Section 5, Calculating Energy Savings**, provides simple methods for carrying out such calculations.

— The final step in evaluating an energy conserving option is to weigh the saving it can achieve against its cost. This Guide does not address cost estimation since it is assumed that this is an area in which most members of the design team are already well versed. On the other hand, methods of weighing the **present costs** of energy conserving options against their **future savings** are less well known. **Section 6, Cost-Benefit Analysis**, presents a number of such methods with comments on the advantages and disadvantages of each.

— **Appendix A, Design Data**, provides various types of data which are useful in applying the above steps.

Unfortunately the presentation of these steps is less than comprehensive. This is because the state of knowledge in the field of energy consumption in buildings is incomplete. For example while the effect of building mass in reducing a building's energy consumption is understood (and presented in this Guide) in a qualitative way, generally accepted methods of quantifying this effect have yet to be developed. **Section 3** therefore, is unavoidably lacking in quantitative information.

On the other hand, **Appendix B, Quantifying The Benefits of Mass**, presents an approach which, although its accuracy cannot be vouched for by the authors or sponsors of this Guide, has received recognition in a model building regulation.

1.5 Units of Measurement

SI (Système International) units are used throughout this Guide.

A special note regarding thermal resistance values is necessary. These values have traditionally been referred to simply as "R values" to avoid the rather lengthy full designation of the units — $ft^2 \cdot °F \cdot hr/BTU$ or $m^2 \cdot °C/W$. With the introduction of SI measurement in Canada, insulation manufacturers adopted the practice of distinguishing between imperial and SI thermal resistance values on packages by designating the latter as "RSI" values. As SI measurement becomes more firmly established in the building industry, the need for this practice is decreasing. Therefore the term R value is used throughout this Guide even though the SI value (i.e. $m^2 \cdot °C/W$) is intended.

Appendix A includes a list of commonly required factors for converting between imperial and SI measurement.

SECTION 2
BASIC PRINCIPLES OF BUILDING PHYSICS

This Section outlines the fundamental principles of physics which govern the performance of a building's envelope or outer shell. As was pointed out in Section 1, the higher priority we are forced to give to energy considerations in designing and constructing buildings will result in the introduction of new materials, techniques and practices. A basic understanding of building physics principles is needed in order to select those measures likely to be most effective in reducing a building's energy consumption and to avoid those measures likely to cause problems affecting a building's durability or serviceability.

Main Points

- The function of the building envelope is to separate the interior environment from the exterior environment.
- The degree of separation is a design decision which depends on, among other things, an economic trade-off between the present cost of improving the envelope and the future cost of energy for space conditioning.
- As the desirable degree of separation is driven upward by higher energy costs, the potential for durability and maintenance problems is increased. This is exacerbated by the present trend toward higher interior humidity levels.
- The main envelope-related characteristics of a building which determine its energy consumption are its form, its size, the thermal resistance of its various elements, its airtightness and the window area and orientation.
- As thermal resistance is increased each added unit of resistance reduces heat loss less than the preceding unit so that for each part of the building there is an economic optimum thermal resistance level beyond which further increases do not produce savings commensurate with their cost.
- Thermal bridges — conductive materials penetrating a major portion of the thickness of the envelope — not only result in additional energy consumption but also cause internal cold spots which can, in turn, cause condensation and related deterioration of adjacent material. Thermal bridges should therefore be avoided if possible and properly detailed if unavoidable.
- Leakage of interior air outward through the building envelope results in deposition of significant quantities of condensation and is a primary cause of moisture-related building problems. These problems can be avoided if a high degree of airtightness is built into the building envelope. Masonry and concrete assemblies lend themselves to effective details to achieve this.
- The incorporation of insulation in a building assembly reduces its ability to dry itself should rain penetration or exfiltration/condensation occur. Correct selection of construction type and proper detailing to avoid such phenomena is therefore important.

2.1 Energy Conserving Buildings: The Envelope Is Only One Large Component

There are many building operation practices which contribute to the waste of energy in buildings. Some common ones are —

- uneven distribution of heat resulting in opening of windows to control local overheating;
- excessive ventilation;
- uneven or excessive cooling;
- simultaneous heating and cooling;
- inefficient combustion equipment;
- continuous distribution and careless usage of hot water.

Each can be a large factor, and means of avoiding each can be and should be considered first on its own economic merits. Lack of attention to one does not greatly alter the importance of attending to another. Poor furnace efficiency, for example, increases the cost of delivered heat and thus increases the saving achievable by proper envelope design, but both remain independently worth attention. Similarly, the presence of a large window does not alter the merits and economics of making the adjoining wall thermally efficient. Of course, the imposition of an "energy budget" — almost always an arbitrary rather than an economic level in individual application — may suggest that the wall be boosted in thermal resistance, or the window area be reduced or other "trade-offs" be made to fit the imposed level. Nevertheless, concerning economic realities alone, each part loses costly energy that is worth restricting to some point of diminishing returns.

For example, airtightness has become particularly important with increasing concerns about air quality, higher humidity, exhaust air heat recovery and avoidance of damaging amounts of condensation. However just because air leakage accounts for a higher percentage of energy consumption in a well insulated building does not increase the already high economic incentive to reduce air leakage. A gigajoule saved is a gigajoule saved whether it constitutes 1% or 100% of the building's energy consumption.

Operation of the building is just as important in energy terms as are the built-in provisions of equipment and envelope.

In summary, energy consumption will be economically minimized to the benefit of the owner and the country only when all three elements are brought together:

1) efficient operation of a —

2) properly designed and executed mechanical system installed in a building with a —

3) well insulated and reasonably airtight envelope

The third factor is the main subject of this Guide.

2.2 Function of the Building Envelope

The building envelope's primary function is to separate the indoor environment from the outdoor environment. It cannot, in fact, act as an absolute separator, but, rather, it must restrict, to some degree, the transfer from one environment to the other of a number of environmental constituents including the following:

— heat energy by itself (including solar radiation)
— air (and its attendant transfer of heat energy and water vapour)
— water vapour by itself (driven by vapour pressure)
— precipitation (driven by wind, gravity or capillarity)

(There are others, such as pollutants; but the above are the ones most directly related to the scope of this Guide.)

The need to restrict these transfers is related to the desire to control the interior environment, which is the reason we build buildings. The degree of restriction provided by the envelope is inter-dependent with the other available means of environmental control. For example, a building with an envelope which provides little restriction to the outward flow of heat in winter can still be kept comfortable if the heating plant is large enough and sufficient fuel is provided to keep the heating plant running. The design of the envelope therefore is dependent, in part, on an economic trade-off between the cost of making it more restrictive to heat flow and the cost of the heating plant and the fuel likely to be consumed over the life of the building.

The envelope's ability to restrict these transfers is also closely related to its own durability. As will be seen in subsequent subsections of this Guide, attempts to make the envelope more restrictive to heat transfer, without proper attention to also restricting water vapour transfer, can lead to premature deterioration of the envelope or excessive maintenance costs.

The following subsections examine each of the above transfers and discuss how each is influenced by and influences the envelope design.

2.3 Heat Transfer

2.3.1 Heat Transfer Principles

The rate of conductive heat energy transfer or flow through a portion of building envelope can be expressed —

$$q = \frac{A \cdot \Delta T}{R} \qquad (2.3.1)$$

where q is the flow rate (W),
A is the surface area of the portion of envelope (m^2),
ΔT is the difference in temperature from inside to outside (°C), and
R is the total thermal resistance of the materials making up the portion of envelope ($m^2 \cdot °C/W$). (Thermal resistance is discussed in Subsection 2.3.3)

The total heat energy transferred over a period of time can then be expressed —

$$Q = \frac{A \cdot \Delta T_{avg} \cdot t}{R} \qquad (2.3.2)$$

where Q is the total energy transferred (W•hr),
t is the length of the period of time being considered (hr.), and
ΔT_{avg} is the average temperature difference over that period of time.

If the period of time being considered is the entire heating season then the factors $\Delta T_{avg} \cdot t$ in Equation 2.3.2 can be approximated by —

$$\Delta T_{avg} \cdot t = 24\ D \qquad (2.3.3)$$

where D is the degree-day accumulation over the heating season.

Degree days are calculated by accumulating the differences between 18°C and the mean temperature for every day in the year when the mean temperature is below 18°C. When this is done over several years for a particular location an average annual value is derived which is an indication of the severity of winters in that location. (Degree day values for several locations in Canada, as found in the Supplement to the National Building Code of Canada, 1980, are given in Appendix A.) Substituting 24D for $T_{avg} \cdot t$ involves the arbitrary assumption that the indoor temperature is always 18°C throughout the heating season. However experience has shown that the degree-day value is a convenient expression of climatic severity which, if used properly, can give reliable results in annual conductive heat loss calculations for small buildings with simple space conditioning systems. This is perhaps attributable to the fact that, although interior temperatures are usually higher than 18°C (which would result in higher degree day values), the tabulated values include some portion which accumulates in the late spring, summer and early fall when the heating system is shut off. The two errors apparently compensate for one another.

Therefore, the annual heat loss can be expressed —

$$H_c = \frac{24A \cdot D}{R} \qquad (2.3.4)$$

where H_c is the annual heat loss (W•hr) through area A due to conduction.

However not all heat energy which flows out through the building envelope in winter is necessarily originally purchased for space heating purposes. Some of it is free solar energy which enters through the windows. Some of it is purchased as electrical energy for the operation of lights, appliances, business machines, etc. Some of it is originally purchased as food and converted to heat energy by the activities of the occupants. Because it is not purchased specifically for space heating purposes all of the energy falling into these categories is sometimes referred to as "free heat". The amount of free heat as a percentage of the building heat loss varies considerably with the type of occupancy.

Equation 2.3.4 does not attempt to distinguish between purchased and "free" energy. Nor does it reflect the dynamic effects through which the thermal inertia of massive buildings can make secondary but appreciable reductions in energy consumption. These will be dealt with in subsequent sections. Nevertheless, Equation 2.3.4 does demonstrate that the three important factors which determine the conductive heat losses through a building envelope are —

— the climate in which the building is located
— the surface area of the envelope
— the thermal resistance of the envelope

2.3.2 Surface Area

From Equation 2.3.4 it is clear that one way to minimize heat losses and gains is to minimize the envelope surface area, A, of the building. Since this energy-saving measure costs nothing — indeed it tends to reduce both first costs and maintenance costs — building developers and designers should not lose sight of this simple fact. Minimizing the ratio of envelope surface area to usable floor area involves the building's basic form, scale and simplicity (flatness) of surface.

Form: While the sphere presents the least surface area for a given volume, the useful size of a building is normally measured in terms of its floor area rather than its volume. A rectilinear building which is square in plan not only is more practical to build than a sphere, but also provides a better ratio of useable floor area to envelope surface area. As shown in Figure 2.1, a building which is rectangular in plan has about 20% more envelope surface area than a square building with the same floor area. Its heating and cooling demands related to losses and gains through the envelope will thus be 20% higher, other factors remaining the same.

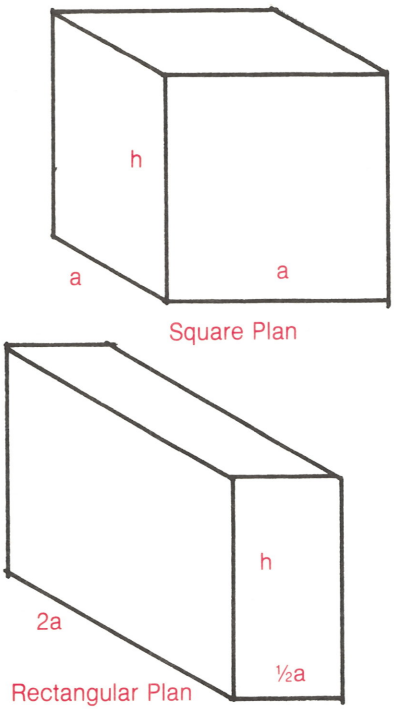
Scale: The size of a building has a greater effect on its surface area/floor area ratio than does form alone. A square two storey house, say, has a much more surface-conserving form than that of a long row house block; but the latter is still more surface-conserving because of size. Its savings in envelope surface area per unit of floor area or per dwelling approaches 40% of that of the two storey house as the row block becomes longer. Similarly a much higher, longer, deeper rectangular block would become more surface conserving than a square-in-plan office building.

Simplicity of Surface: A radiator is deliberately designed with convoluted surfaces in order to increase its surface area and thus its ability to dissipate heat. Some buildings (Figure 2.2) almost seem to have been designed with the same objective in mind. Such complex surfaces can double or even triple the envelope surface area and the related heating and cooling demands as compared to a building of similar size and form with basically flat surfaces.

While it is unlikely that building developers and designers or the public at large would want all future buildings to be flat-sided, square-plan boxes, if the energy costs associated with deviations from this model are born in mind, perhaps the more extreme deviations can be avoided.

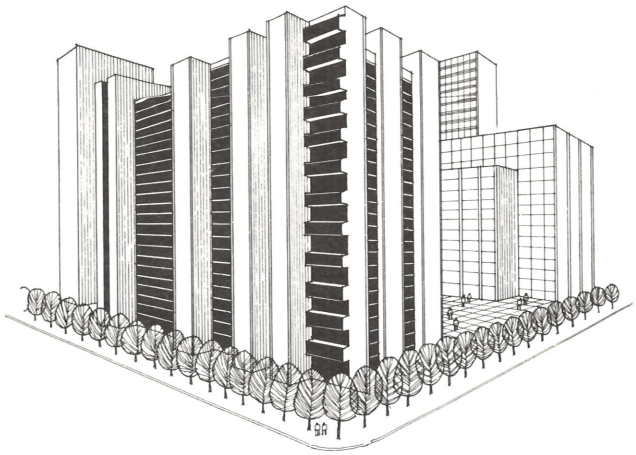
2.3.3 Thermal Resistance

The effectiveness of a building assembly such as a wall or roof in resisting the flow of heat under static conditions is defined as its thermal resistance or R value. This property can be measured for individual-homogeneous materials on the basis of a unit thickness (say 1 mm) and can then be used to compare the relative insulating values of various materials. In this case it should properly be called thermal resistivity but the terms "thermal resistivity" and "thermal resistance" are often used interchangeably. The thermal resistance of a one-material component can be approximated by multiplying its resistivity by its thickness. The thermal



	square bldg	rectangular bldg
floor area	a^2	a^2
surface area (excluding floor)	$4\,ah + a^2$	$5\,ah + a^2$

Figure 2.1 Square Plan vs. Rectangular Plan Buildings, with same floor areas and height.



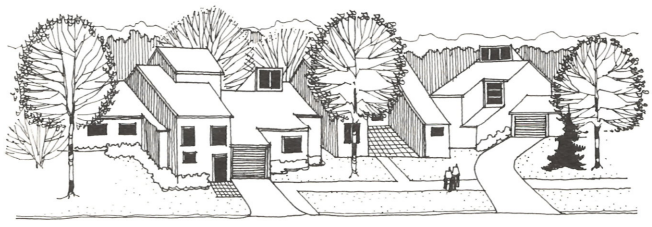


Figure 2.2 Radiators in The Sky

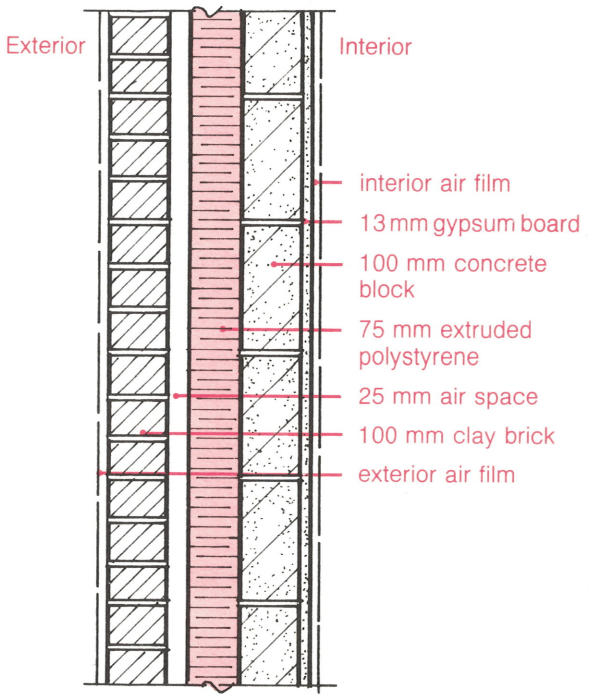
resistance of a building assembly is determined by adding the thermal resistance of its components. Figure 2.3 gives an example of such a calculation. The thermal resistance of an assembly can be thought of as the number of Celsius degrees of temperature difference between its warm and cold sides needed to drive one watt-hour of energy through one square metre in one hour. The units are therefore $m^2 \cdot °C/W$. Thermal resistance is represented by the symbol "R". Thermal resistance values for various construction materials are given in Appendix A.

An insulating material achieves high thermal resistivity by interfering with convection (the carrying of heat by air currents) and radiation (the transfer of heat across empty space with no carrier needed), while presenting very little solid material to allow heat flow by conduction (molecule-to-molecule agitation through solids). The lighter and less solid the fibrous or cellular insulation material the more effective it is, down to the point where it becomes too open textured and convection and radiation transfers begin to increase.

Note that the calculation in Figure 2.3 includes R values for air films and the air space. Adjacent to the exposed surfaces of any building assembly there are very thin films of still air which contribute a small amount of thermal resistance. The exterior film is assumed to contribute less due to the scouring action of wind. Air spaces within the assembly also contribute thermal resistance. The exact amount of that contribution depends on the thickness and other dimensions of the space (which affect the convective heat transfer) and on whether or not the space is faced with reflective materials (which affects the radiative heat transfer). The values given in Appendix A are somewhat simplified but are adequate for most purposes.

A common mistake in R value calculations is to assume that reflective films contribute thermal resistance in all building assemblies which incorporate them. In fact they only contribute when they are facing an air space since it is only in this circumstance that radiative heat transfer becomes at all significant.

While all materials have some thermal resistivity value, those of most structural, cladding and finish materials, including masonry and concrete, are quite low. Thus, in the Canadian climate with today's energy costs, all building assemblies making up the exterior envelope of a building must incorporate insulation to even approach a realistic thermal resistance level. The result of the presence of an effective insulating material in an assembly, in winter, is that the materials on the interior side of the insulation are consistently warmer and those on the



component		R value ($m^2 \cdot °C/W$)
interior air film	—	0.120
gypsum board	—	0.081
concrete block	—	0.125
ext. polystyrene	—	2.603
air space	—	0.171
clay brick	—	0.074
exterior air film	—	0.030
		$\Sigma R = 3.20\ m^2 \cdot °C/W$

Figure 2.3 Calculation of the Thermal Resistance of a Building Assembly.

exterior side are consistently colder. The temperature at various points within the assembly can be calculated by apportioning the overall inside-to-outside temperature drop (which is determined by the interior and exterior conditions) in proportion to the thermal resistance of the various components of the assembly. Figure 2.4 illustrates the procedure.

Figure 2.5 shows temperature profiles for five cavity walls of essentially the same construction but with various amounts of insulation ranging from uninsulated to highly insulated. It is apparent that, even with relatively modest amounts of insulation, most of the temperature drop takes place across the insulation and that such choices as lower density concrete or cellular concrete for the other components would have little effect on steady state temperatures.

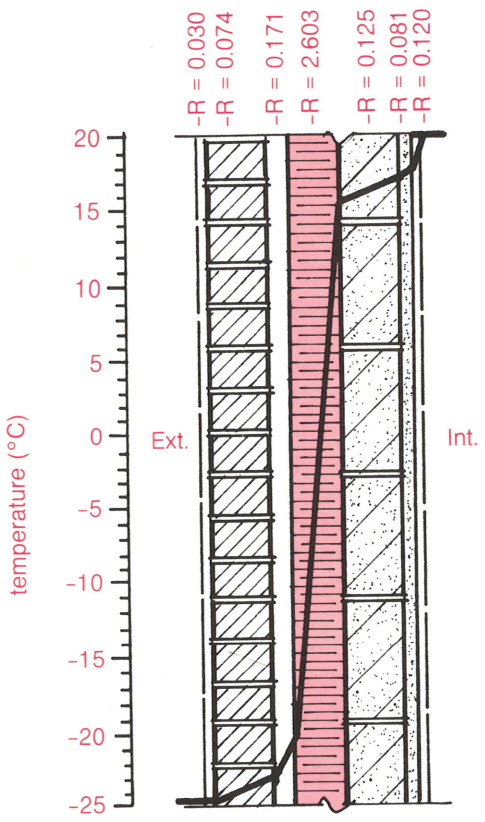
Generally, it is economical to let structure be structure and insulation be insulation, although the lightweight structural materials sometimes help achieve a last bit of R value where space is at a premium or where a thermal bridge should be covered, as discussed later.

The addition of even minimal insulation increases the interior surface temperature from 11°C (Wall A) to 16°C (Wall B). It also drops the average temperature of the outer wythe from -20°C to -23°C. The construction detailing must allow for more contraction/expansion of the outer wythe but less for the inner. The lower average temperature and lower slope of the temperature profile of the outer wythe also results in less potential for drying that wythe in the event that it should come in contact with moisture from internal or external sources.

The addition of further insulation (Walls C, D and E) has a less pronounced effect on the average temperatures and temperature profiles of the outer wythe than does the first addition. Thus the potential for problems of the types hinted at above and discussed more fully in subsequent subsections exists in all insulated assemblies. This potential is increased in highly insulated assemblies but not markedly so.

2.3.4 Insulation Placement

Figure 2.6 illustrates a sixth version of the cavity wall of Figure 2.5. It has the same overall thermal resistance as Wall D but the insulation is placed on the interior side of the structural components. Now the entire structure is at or near the outdoor temperature. Expansion/contraction detailing is therefore important for both wythes. Moreover, drying actions are very weak. Such an arrangement usually makes significant "thermal bridges" unavoidable where cross-walls, floors and roofs must penetrate the insulation layer to connect to the outer wall structure.



R_n (m²·°C/W)	0.120	0.201	0.326	2.929	3.100	3.174
$\frac{R_n}{R_t}$	0.037	0.063	0.102	0.913	0.968	0.991

$T_n = T_i - (\frac{R_n}{R_t})\Delta T$

(°C)	18.3	17.2	15.4	-21.1	-23.5	-24.6

$\Delta T = T_i - T_o = 45°C$
$R_t = 3.20$ m²·°C/W

where R_n — total thermal resistance to outer edge of n'th component
R_t — total thermal resistance of wall
T_n — temperature of outer edge of n'th component
T_i — inside temperature
T_o — outside temperature

Figure 2.4 Calculation of Temperature Profile in a Building Assembly

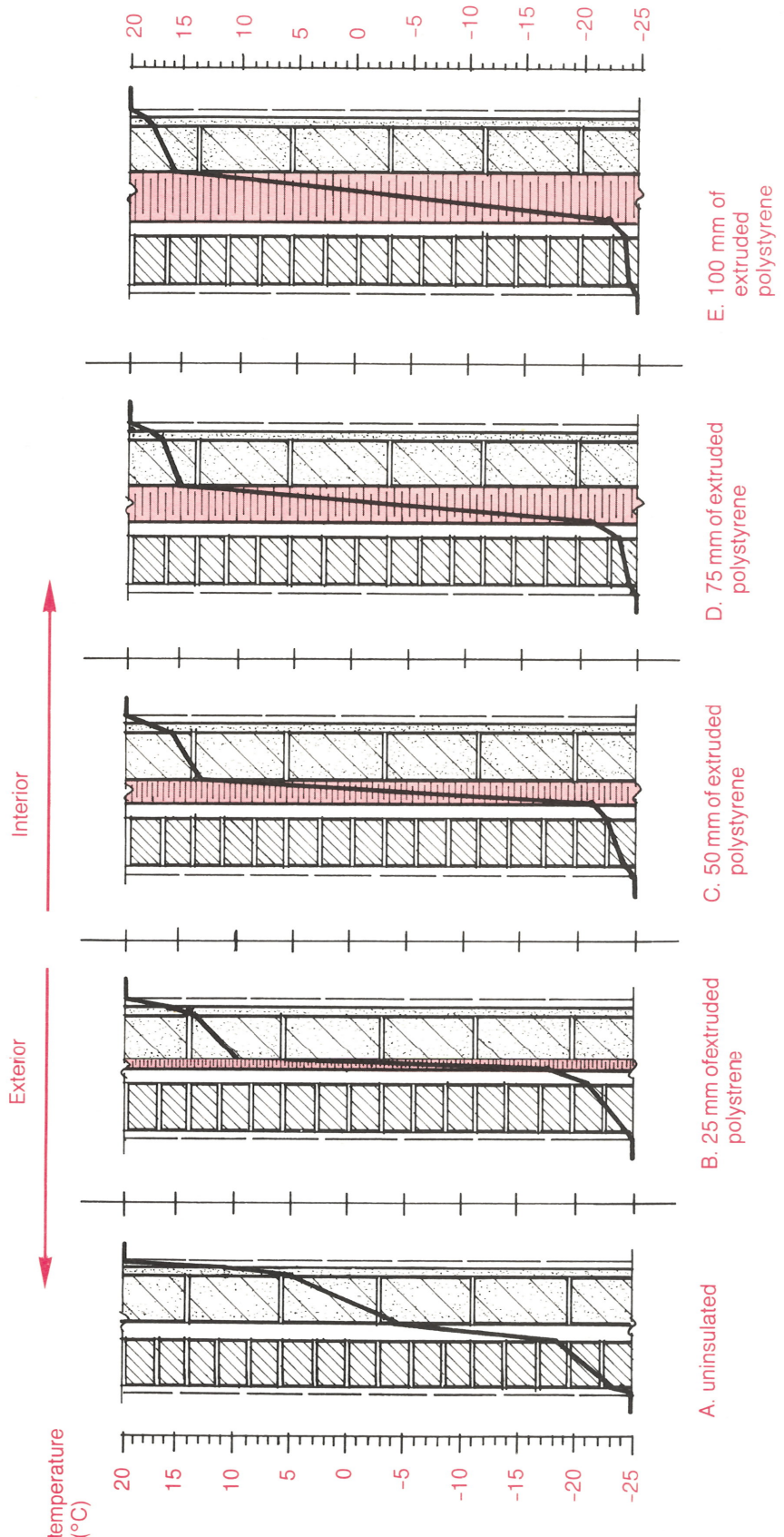


Figure 2.5 Temperature Profiles on a Typical Cold Winter Day for Five Cavity Walls with Various Amounts of Insulation.

(These are discussed in Subsection 2.3.5). Finally, it will be shown in Section 3 that any potential heating energy benefits which might be derived from the mass of the structure will be minimized with this arrangement. In sum, although this arrangement is by no means uncommon in Canadian buildings, there are many reasons why it should be avoided, as outlined above.

2.3.5 Thermal Bridges

"Thermal bridges" are points or components with relatively low thermal resistance which intrude or "bridge" through the insulation layer of the building envelope. The almost unavoidable small thermal bridges (ties, hangers, shelf angles, insulation fasteners) need not contribute significantly to the overall heat losses or gains. They can also be placed or detailed to avoid depressing temperatures at the interior surface or other places prone to condensation and related corrosion or other degradation. Much more serious, in the Canadian environment, are the large thermal bridges commonly exemplified by structural floor, cross wall and partition intrusions through the envelope's insulation.

As indicated above, the concern with the small unavoidable thermal bridges is not so much the energy which is lost through them, as the fact that they create cold spots on the interior surface of the envelope where condensation and related corrosion or other degradation can occur. This tendency can be minimized if the inner end of such a bridge incorporates or is connected to a large conductive area and the outer end is relatively smaller and more resistive. Although it is difficult to quantify the effect, such a detail tends to raise the temperature of the bridge without significantly increasing the heat flow through it since the inner end tends to collect heat at a faster rate than the outer end dissipates it. (Fig. 2.7) Thus the temperature of the bridge material rises until equilibrium is reached at a higher temperature.

Although no reliable method of calculating heat flows and temperatures in and around thermal bridges has been developed, actual wintertime temperature measurements on large thermal bridges, such as, concrete floor slabs and cross-walls bridging interior-side insulation, have found interior surface temperatures at these points as much as 21 °C below the average temperature of surrounding surfaces (1). Such points are certain to be cold enough to cause condensation of water vapour from interior air even at moderate relative humidity. Perhaps the worst type of thermal bridge is created by the practice of cantilevering the floor slab beyond the wall to form a balcony (Figure 2.8A). The balcony thus acts as a large fin draining heat away from the wall and depressing interior surface temperatures even further

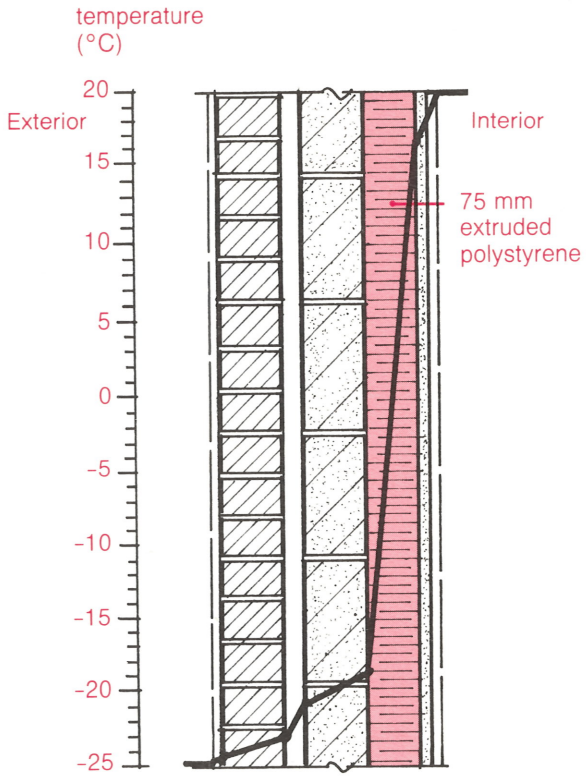


Figure 2.6 Insulation Placed on Interior

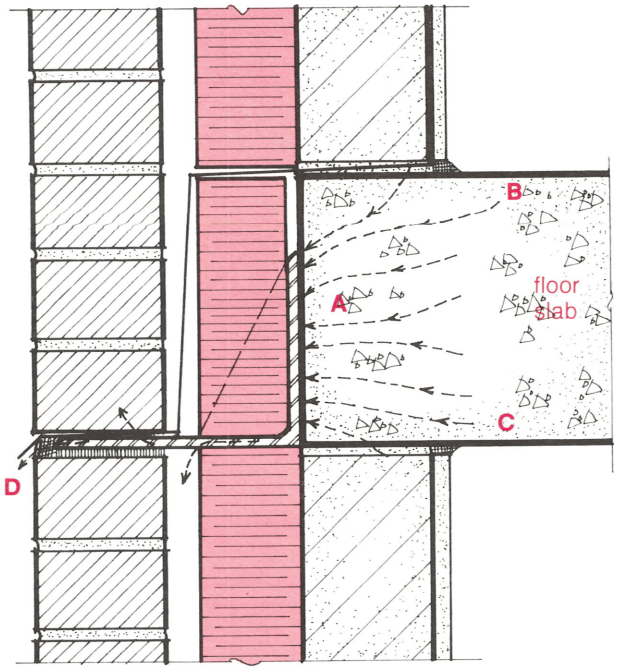


Figure 2.7 An Unavoidable Thermal Bridge Properly Designed and Treated (temperatures at A, B, and C remain warm because the steel angle's pickup area A is large and conductive while its heat releasing area D is relatively restricted)

— below the freezing point in some cases. Even if the interior air has low relative humidity, this will lead to some condensation; and, if the humidity level is allowed to go higher, such problems as stains, mould growth, curling floor tile and peeling finishes can result. These problems will be more severe in colder climates. (The psychrometric relationships are outlined in Subsection 2.4.2.) Also the amount of heat loss through a thermal bridge of such large cross-section can be very significant.

Wherever possible the insulation should be placed outside the inner wythe and continued past the ends of floors, cross-walls, partitions and roofs. One practical way to avoid the thermal bridging effect at balcony slabs is to support the balconies from the ground with only minimal tying into the building (Figure 2.8B).

2.3.6 Diminishing Returns — A Fundamental of Insulation Economics

Doubling the R value of an envelope halves the rate of heat loss through it; doubling it again halves just that remaining half, i.e. reduces the original loss rate by only one-quarter. Every added unit of resistance reduces heat flow, but each unit reduces it less than the preceeding unit. The principle of diminishing returns is fundamental to any economic determination of how much insulation to use. Section 5 deals fully with the approaches to such determinations. Here, it is useful to illustrate the principle by means of the example walls in Figure 2.5. Recalling from Equation 2.3.4 that heat loss is inversely proportional to thermal resistance, it is therefore possible to indicate the relative heat loss potentials of these walls by the reciprocals of their R values. These values are plotted against insulation levels in Figure 2.9. Clearly the first increment reduces heat loss a great deal, the next three achieve increasingly less and the last increment makes very little difference. On the other hand, if Figure 2.9 were drawn with the cost of energy rather than amount of energy on the vertical axis, its vertical scale might be greatly exaggerated (depending on what cost was used) and the case for the last increment might look somewhat better. Some method of weighing the cost of each increment of insulation against the value of the energy it is likely to save, must be a part of the determination of economic insulation levels. Various methods having various degrees of complexity are outlined in Section 6.

2.3.7 Independence of Insulation Levels

Consideration of Subsection 2.3.6 reveals that, in the absence of imposed regulations, there are basically only two sets of information needed to select an economic insulation level for any part of the building envelope. First, the cost of achieving various R values for that part of the envelope must be estimated.

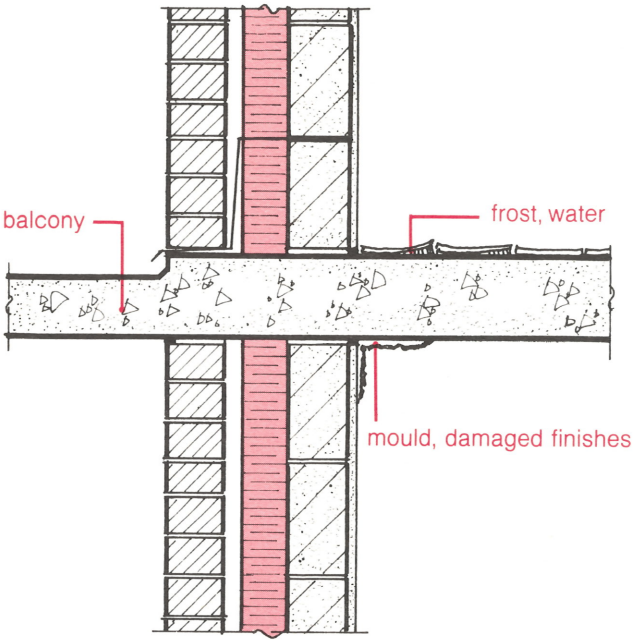


Figure 2.8A Effect of Thermal Bridge When Indoor Relative Humidity is Appreciable (above 20% RH in midwinter)

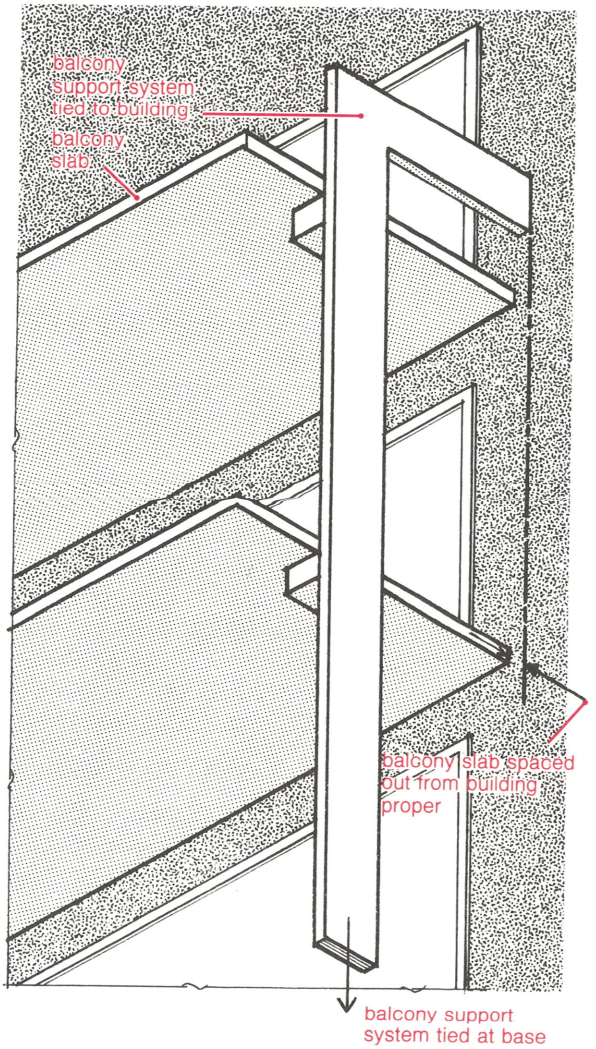

balcony support system tied to building
balcony slab
balcony slab spaced out from building proper
balcony support system tied at base

Figure 2.8B Balconies Supported from Ground to Avoid Thermal Bridges

Second, some value must be placed on the **purchased** energy that will be lost through that part at various R values. This second step is quite complex and will probably involve estimating such indeterminate parameters as the useful life of the building, the future cost of energy, the value of money (the discount rate or opportunity cost), the future rate of inflation, etc. However once values have been assigned to these parameters and values for energy loss at various R values derived, these values need only be weighed against the costs of achieving those R values, using one or more of the methods outlined in Section 6, and an economic R value selected. The advantage of this process is that it can be carried out for each part of the building envelope quite independently and without reference to the other parts. Put another way, for any given set of economic assumptions, each part of the building envelope has an economic optimum R value which is independent of how big or how small a portion of the building envelope that part constitutes and is independent of the R values of the other parts of the envelope. This discussion ignores the possible effect of one component on another due to radiative or convective heat exchange within the conditioned space. However these effects are not likely to be significant in most cases.

If this point seems hard to grasp, consider a 2500 m^2 roof. Whether that roof is on a one storey building and constitutes 80% of the building envelope area, or on a 10 storey building and constitutes 30% of the building envelope area will not affect the cost of insulating it to any given R value; nor will it affect the amount of heat which flows out through that roof in a heating season or over its life. Neither are these affected by what R value is selected for the walls or whether the windows are double- or triple-glazed or, indeed, whether the walls are all glass. As long as the heating system is capable of maintaining the design indoor temperature, the heat loss through the roof in a given climate is determined only by its own thermal resistance. Therefore determining the optimum insulation level for that roof involves only weighing the investment of today's money to insulate the roof against the saving of tomorrow's money which will result from reducing heat loss through the roof. The same applies for the other parts of the envelope, independently.

If an economic optimum R value is determined in this way for each part of the building envelope, then the building as a whole will be at its economic optimum thermal resistance level.

Practicalities intrude upon the above considerations but do not change the independence of each part. For example, taking all parts of the envelope to their optimum R values may require more money in total than is available in the building budget. Since these

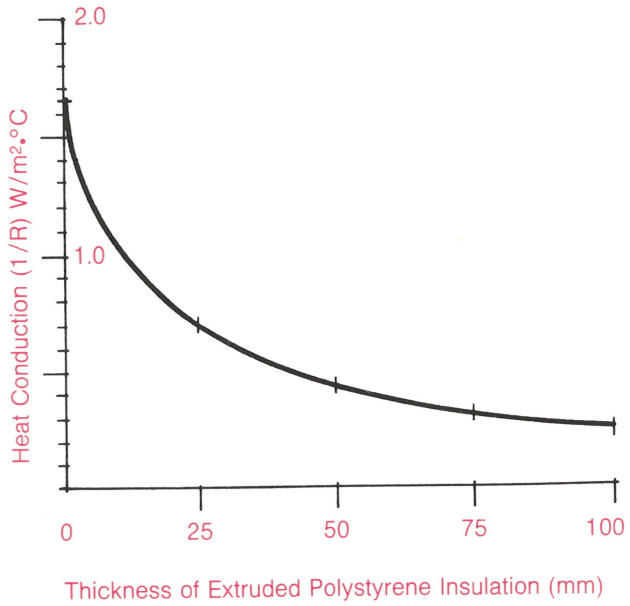


Figure 2.9 Heat Flow Through Example Walls of Figure 2.5.

optima are based on economic analysis, an argument could be made for reducing the size of the building or eliminating some of the amenities in order to reduce the total cost. However, in many cases, the designer may elect to leave some parts of the envelope below the optimum R value. This is best done with those parts such as roofs which are most easily upgraded at a later date when the original economic assumptions are either confirmed or refuted.

Also the building will probably be required to comply with some energy or rate-of-heat loss budget, such as those imposed by building regulations, which might not be met with all parts of the envelope at their economic optimum R values as calculated by the designer. The designer would then logically choose to upgrade beyond its optimum that part of the envelope which would reduce heat loss by the largest amount for the least money, bearing in mind that upgrading a part of the envelope that constitutes only a small portion of the entire envelope area will not accomplish very much total reduction in heat loss.

In both these examples the designer might arrive at the optimum solution to the particular problem, but some parts of the envelope would not be at their economic optimum thermal resistance values.

As was pointed out earlier, determining the optimum thermal resistance is a complex task. Simple formulae, such as that presented in Subsection 6.7, are, at best, crude approximations of the relationships among the various parameters and the values derived using them will be no closer to reality than the values determined or guessed for the inputs. Nevertheless this does not reduce the validity of the concept. The fact that the optimum thermal resistance value is difficult to determine with confidence does not mean that it does not exist.

2.3.8 Insulation "Trade-offs"

Investment in energy conservation can and should be an economically viable proposition if proper planning and design is undertaken. The first steps toward this objective have been taken by regulatory bodies, and are in the form of prescribed building component R values. These R values have been chosen to meet general levels of economic viability while achieving significant reductions in energy use compared with buildings that do not meet these standards.

It will be appreciated, however, that a single R value for a given component in a given area cannot be expected to satisfy every building owner's definition of "sound economic investment". Regulatory bodies generally recognize this shortcoming of the "prescribed R value" approach and offer some latitude in the design procedures: trade-offs are allowed in the choice of R values for the various components of the building, such that the overall heat loss of the building is the same as or less than that which results from using the prescribed R values. The trade-off exercise is particularly useful if the designer finds that some parts of the building envelope can be taken **beyond** the prescribed minimum R values for less cost than required to bring other parts **up to** the prescribed values.

The following example shows how wall and floor R values can be modified to satisfy other criteria while achieving the same (or less) building heat loss as the building with prescribed R values.

Example 1. Acceptable Trade-offs

Given

Description of the structure:

- 6 storey apartment, below grade unheated parking
- 15 × 60 × 16 m tall
- floor area exposed to unconditioned space — 900 m^2
- roof area — 900 m^2
- net opaque wall area — 1440 m^2

Construction:

Walls — Masonry cavity wall, insulated in cavity
Floors — 150 mm reinforced concrete slab insulated on underside
Roof — 150 mm reinforced concrete flat slab with inverted membrane roof.

Design Criteria:
Assume the following R values are prescribed by regulations:

Floors: 2.83
Walls: 2.83
Roof: 2.83

Trade-off Analysis

Calculation of Rate of Heat Loss Budget for Insulated Building Envelope

Assembly	Area (A)	Prescribed R Value	Heat Loss Factor (A/R) W/°C
Walls	1440	2.83	509
Roof	900	2.83	318
Floor	900	2.83	318
Total Rate of Heat Loss Budget			1145 W/°C

Meeting the Rate of Heat Loss Budget

The designer has the option of selecting construction assemblies which provide the prescribed R values **or** trading-off R values from one assembly to another while not exceeding the budgeted heat loss for the entire structure.

a) Prescribed Levels

To achieve R 2.83, typical assemblies are as follows:

Walls — require 76 mm Type 2 polystyrene or fibreglass cavity insulation — R 2.89
Roof — require 76 mm Type 4 polystyrene — R 2.91
Floor — require 83 mm rigid fiberglass insulation — R 2.90

(Note: A number of materials and combinations can be used to achieve these R values — these are **examples only**.)

b) Looking at Trade-Offs while Meeting the above Heat Loss Factor

The designer in this example may find that he can accommodate more roof insulation for little additional cost, but there may be design constraints, such as space, which make it desirable to limit the thickness of the masonry cavity wall. He thus decides to go up to R 3.35 for the roof insulation. By trial and error, assemblies may be chosen for the walls and floor such that the total rate of heat loss is less than the 1145 W/°C calculated above. One possible combination in this example is:

Walls — 38 mm urethane insulation — R = 2.67
Roof — 89 mm Type IV polystyrene — R = 3.35
Floor — 76 mm rigid fibreglass — R = 2.72

Check overall rate of heat loss:

Assembly	Area (A)	R	Heat Loss Factor (A/R)•W/°C
Walls	1440	2.67	539
Roof	900	3.35	269
Floor	900	2.72	331
Total Rate of Heat Loss			1139 W/°C (<1145)

With such a design, the designer has maintained the wall thickness while achieving a level of energy conservation that is commensurate with that targeted in the code.

Some Trade-offs Cannot Be Done

One of the more tempting trade-offs is to leave one component of the envelope totally uninsulated and overdesign the insulation of the other components to make up for the poor performance of the uninsulated component. This practice is seldom economic and may not be possible. Often, there is not enough energy left to be saved by the other components to make up for the poorly insulated component.

Example 2: Trade-off Which Cannot Be Achieved

Given: — The same building as in Example 1,
— The designer would like to avoid putting insulation in the wall.

Trade-off Analysis
The R value of the uninsulated cavity wall is about 0.77 m^2•°C/W. With 1440 m^2 of wall area, the rate of heat loss for that wall would be 1870 W/°C.

From the calculations in the previous example the following table is drawn up:

Assembly	Rate of Heat Loss (W/°C)	
	With Prescribed R values	With "Trade-off" R values
Walls	509	1870
Roof	318	?
Floor	318	?
Total	1145	1870

It will be recognized that even if the roof and floor had **infinite** insulation they could not make up for the poor wall performance. The trade-off cannot be achieved given the condition that the walls have no insulation.

The above example illustrates two important points that are discussed in earlier sections.

1. The cost/benefit economics of each component is independent of the other — unreasonably high insulation of one or more components cannot be justified by the poor performance of another component.

2. Whereas there is almost no limit to the amount of heat energy that can be **wasted** by one component (given a large enough heating plant), there is a limit to how much can be **saved** by insulating other components (i.e., the heat loss that is left).

Some Trade-offs Work "Too Well"

When there are large differences in the areas of different building envelope components or where regulations allow windows to be included in the trade-off, it is possible to make large reductions in some R values and still remain within a given rate of heat loss budget.

Example 3
Given:
A single storey manufacturing building, 30 m × 30 m with 5.5 m high walls, 70 m^2 of window area and 20 m^2 of door area.

Design Criteria:

Assume the following are prescribed by regulations:

Roof R value — 2.5
Wall R value — 2.5
Windows — double glazed (R 0.3)

Calculation of Rate of Heat Loss Budget

Assembly	Area	Prescribed R Value	Heat Loss Factor (A/R)•W/°C
Roof	900	2.5	360
Windows	70	0.3	233
Wall	570	2.5	228
Total Rate of Heat Loss Budget			821 W/°C

If the designer elects to increase the roof R value to, say, R 4.0 without changing the window area, the wall R value could be reduced as follows:

Assembly	Area	R Value	Heat Loss Factor (A/R)•W/°C
Roof	900	4.0	225
Windows	70	0.3	233
Wall	570	1.6	356
Total Rate of Heat Loss			814 W/°C (<821)

If the designer also decides that the window area can be reduced by, say 25%, a further reduction in the wall R value is possible:

Assembly	Area	R Value	Heat Loss Factor (A/R)•W/°C
Roof	900	4.0	225
Windows	52	0.3	173
Wall	588	1.4	420
Total Rate of Heat Loss			818 W/°C (<821)

Even further reduction in the wall R value is possible with further reduction in window area, further increase in roof R value, or increasing the number of layers of glazing. However, a cost-benefit analysis (see Section 6) should be undertaken to determine if such reduced R values will be in the best interests of the building owner over a period of time. Indeed it is likely that, by most economic criteria, higher R values for the walls would be justified. However, this example does indicate what can be done in the area of code compliance using this type of trade-off. When initial construction budgets predicate taking steps such as those outlined in this example, the possibility of upgrading the thermal resistance of the walls at a later date should be borne in mind.

2.4 Air Leakage

2.4.1 Relationship with Ventilation and Energy Consumption

Definitions

Air Leakage: Uncontrolled exchange of air between the indoor and outdoor environments through unplanned openings in the building envelope.

Ventilation: Controlled exchange of air between the indoor and outdoor environments through planned openings (including ducts) in the building envelope.

A certain amount of air exchange between the indoor and outdoor environments is necessary in order to control indoor air quality. The amount varies from building to building depending on such factors as size, type of occupancy, rate of generation of humidity and rate of generation of pollutants. However, for any given building, there is a desirable amount of air exchange. If air leakage is less than that amount, then it need not add to the building's heating and cooling loads. Nevertheless there are good economic reasons why air leakage should be reduced to the greatest extent practical —

- Because it is accidental, it is highly unlikely that air leakage will provide just the right amount of air exchange — it will either provide too much or too little. Therefore a ventilation system must be provided. Because air leakage cannot be accurately predicted it is usually not taken into account in designing the ventilation system, i.e. the ventilation system is designed to provide all the required air exchange. Thus the air leakage becomes extra air exchange and does add to the heating and cooling loads.

- Many ventilation systems now incorporate devices for recovering the heat in the outgoing air. Such devices can only work on the ventilation component of air exchange; i.e. those portions of the outgoing indoor air which are contained in ducts. Outward air leakage thus represents an irretrievable heat loss.

- Air leakage inward through the building envelope (infiltration) can create discomfort in much of the perimeter floor area. A common reaction is to set thermostats at higher temperature to compensate. This causes a substantial increase in heat loss.

- Air leakage outward through the building envelope (exfiltration) carries with it internally-generated water vapour which is deposited on cold components of the structure as condensation and can eventually lead to their deterioration. This is dealt with more thoroughly in Subsection 2.4.2.

Air change, the sum of leakage and intentional ventilation, is properly considered as a distinct component of a building's heat losses or gains, counted separately from the envelope's transmission losses dealt with in Section 2.3. The rate of heat loss by air change can be calculated if the volumetric air change rate is known. First the "sensible" heat loss rate is —

$$q_s = 0.335\ n \cdot v \cdot \Delta T \qquad (2.4.1)$$

where q_s is the rate of loss of sensible heat due to air exchange (W),
n is the number of exchanges of the complete volume of air in the building per hour,
v is the volume of the building (m^3), and
ΔT is the difference in temperature from inside to outside (°C)

That is, each cubic metre of air coming in must have heat added to it to raise its temperature to the desired indoor temperature. Considered another way, each cubic metre of air escaping carries with it that amount of heat; the air and the heat must be replaced.

A further heating burden arises because the incoming air in winter is rather dry; i.e. its absolute humidity is low although its relative humidity (RH) at its outdoor temperature is usually high. (The psychrometric relationships follow shortly). Water vapour will usually be added accidentally or intentionally to raise the incoming air's humidity. That water may be free or essentially so, but the "latent heat of vapourization" taken to release water vapour into the air will be absorbed from the indoor air and must be replaced to maintain its temperature at the desired level. (The opposite holds true in summer months: removing excess humidity from the warm outdoor air is a part of the "cooling load" energy demand). This additional "latent" heat loss due to air change is:

$$q_e = 823\, n \cdot v \cdot \Delta W \qquad (2.4.2)$$

where q_e is the rate of heat absorption to vaporize water (W), and
ΔW is the difference in humidity ratio between the indoor and outdoor air (kg water/kg dry air)

Unfortunately, the peak rate of air change always includes rather indeterminable air leakage as well as somewhat more controllable mechanical ventilation, which makes it difficult to calculate the capacity of the heating/cooling plant to cope with the energy demands created by air change. Building exposures, heights, wind regimes, "stack action" forces operational patterns, sizes and locations are all involved in a complex interplay in any building; the overall effect cannot be reliably calculated. The seasonal average air leakage rates and overall air change rates are even less well known. Hence it is most difficult to assess the energy-saving efficacy of air sealing steps and the cost-benefit economics of constructing airtight envelopes. This is as true for masonry and concrete energy-conserving buildings as for any other, and this Guide can do little beyond referring the reader to the ASHRAE Handbook of Fundamentals (2) and Division of Building Research publications (3,4) which deal with the subject as well as the present state of knowledge permits.

One point must be made: masonry and concrete buildings are often more amenable to practicable airtightening than are other systems of construction. This is because the structural elements normally have relatively large, smooth, flat surfaces to which finishing materials can be tightly fitted and sealed and they are often solid without concealed passages through which air can move as is common in frame types of construction. This is important in terms of energy conservation and can be essential to preventing damaging conditions within the envelope construction as is next discussed.

2.4.2 Deleterious Effect of Air Leakage on the Building Envelope: Exfiltration/ Condensation

Air leakage outward (exfiltration) through the envelope can result in material and structural deterioration in buildings of all types of construction. This is especially true in insulated buildings and may reach destructive levels as indoor humidities become appreciable. As outlined below, the avoidance of costly damage is a primary reason to strive toward airtight construction.

Fig. 2.10 illustrates a rather extreme manifestation of the exfiltration/condensation phenomenon that now must be defined and considered very carefully. This building was designed and constructed as a typical office building but was then "adapted" for service as an art gallery. The adaptation involved simply humidifying its indoor air to 50% relative humidity (RH) to help protect the paintings throughout the winter.

Such office buildings, and large buildings generally, have traditionally tended to operate with generous air change rates and resulting low humidity (10-15% RH) during the heating season. Hindsight suggests that the low humidity has been the principle factor that has forestalled or limited the exfiltration/ condensation effects in such buildings. This particular building was manipulated to operate in a manner seemingly only slightly different from that originally intended — rather powerful humidification was introduced — and became an early example of a

building problem that appears to be on the increase in Canada.

As moist indoor air exfiltrates through leaks in the envelope, it deposits its moisture load as condensate on or in the cold materials. While most building assemblies can tolerate some small amount of this, if the interior humidity is maintained at a high level the amount of such condensation can be large enough to cause problems.

There may not be much demand for 50% RH in our buildings but there is a demand and apparently a trend to operate buildings at 25%, 30% or even 40% RH in the winter rather than the traditional 10% or 15%. In any case, the better controlled and much lower air change rates result in higher indoor RH, intentionally or otherwise. The resulting problems can be avoided or remedied in simple fashion, given an appreciation of the following factors:

- the properties of indoor/outdoor air,
- the forces pushing exfiltration,
- the size and location of air leakage paths,
- the quantities of air flow and the attendant condensation phenomenon and its effects, and
- the drying factors.

- **Properties of moist air**: ASHRAE (2) defines psychrometry as "the branch of physics relating to the measurement or determination of atmospheric conditions, particularly regarding the moisture mixed with the air." Figure 2.11 is a psychrometric chart which shows the relationships among air temperature, relative humidity and water vapour content. Relative humidity is the ratio of the amount of water vapour in air at a given temperature to the ultimate amount it can hold in vapour form at that temperature. Warm air can hold a large amount of water in harmless vapour form; cold air can not.

If the warm indoor air — say 20°C, 35% RH, holding 0.005 kg. of water vapour per kg. of dry air — is cooled to its saturation or "dew point" temperature of 4°C by contact with a cold window or a thermal bridge (line ⓐ - ⓑ in Figure 2.11), then its RH at that point becomes 100%. If the temperature is reduced further or if more water vapour is added to the indoor air, then the excess vapour must condense on that cold surface.

If the warm indoor air exfiltrates through leaks in the envelope and travels over or through progressively colder materials, finally much below its dew point, essentially all of its vapour will condense as liquid water within the envelope. Take for example Wall C of Figure 2.5, redrawn now as Figure 2.12. If a small leak allows air to exfiltrate past the first third of the insulation (either through the insulation or through joints, depending on its type) it will be cooled below its

Figure 2.10 Exfiltration/Condensation

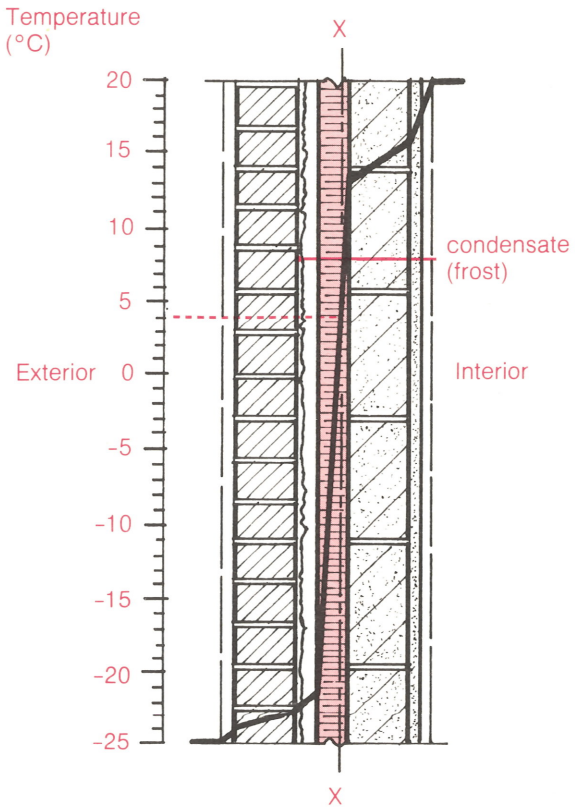


Figure 2.12 "Wall C": Exfiltration Air Will Be Cooled Below Its Dew Point Beyond Plane "X"

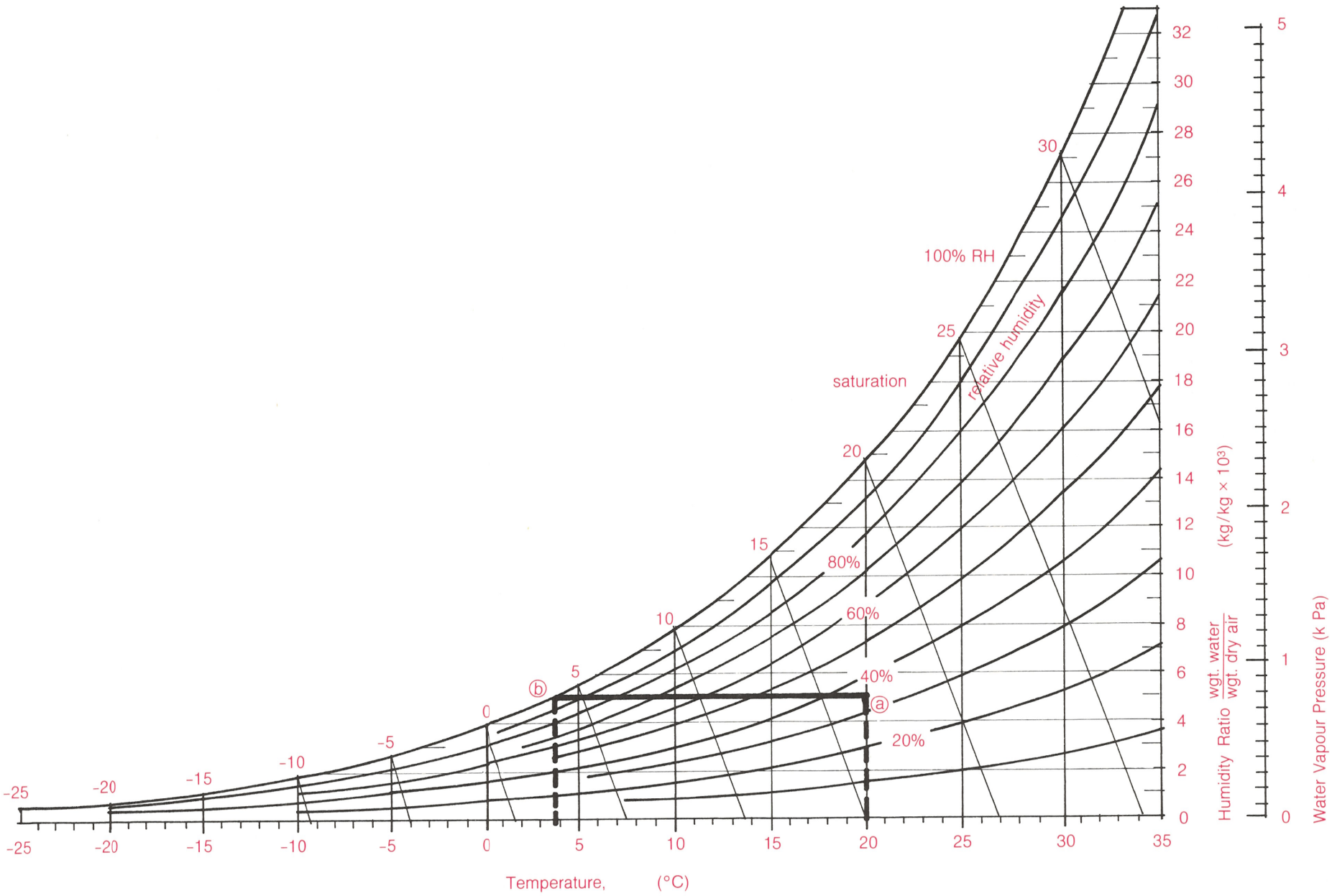


Figure 2.11 Simplified Psychrometric Chart

dew point of 4°C. Now supersaturated, it may deposit some condensation within the insulation or at its interfaces with other materials, depending on its velocity of flow and the structure of the materials, and will enter the air space with considerable visible condensate (fog, frost). As it contacts the outer brick it will be cooled to about -25°C and will drop practically all its remaining moisture in the form of frost on the back of the brick. Eventually the air will pass outdoors at about -24°C, still saturated but able to carry away very little vapour. The quantity of water the small leak of indoor air deposits in the envelope depends only on the foregoing psychrometric relationships, the rate of air flow and the length of time over which it occurs.

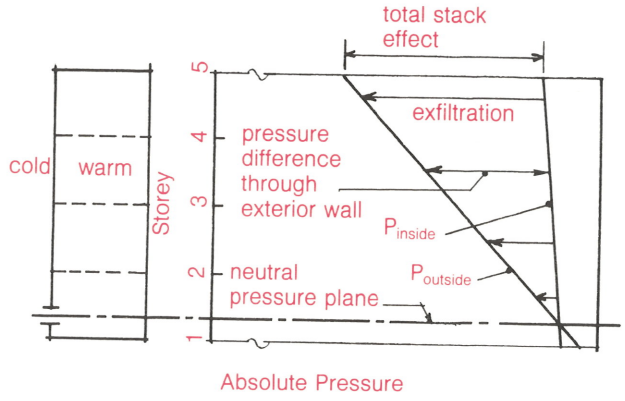
Relatively large leaks change the above relationships somewhat by warming the materials along their paths. This complicates the picture but does not avert the almost-complete deposition of water as liquid condensate within the envelope construction. And of course the energy waste and amount of condensation becomes greater.

- **Differential air pressures across the envelope:**

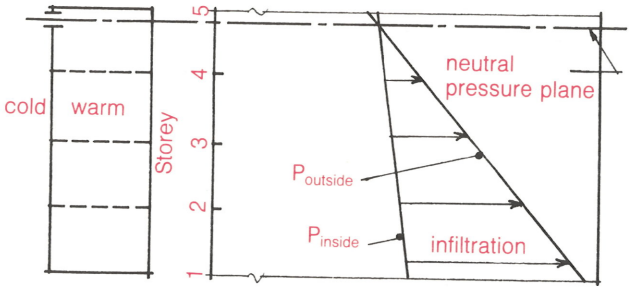
The forces pushing exfiltration through the envelope in winter are due to "stack action" and wind. The former does not exert a large force but it operates 24 hours a day; the latter can exert a large force, operating for long periods in some regions, pushing exfiltration through the lee sides of buildings.

"Stack action" is the buoyancy effect due to the warm indoor air being less dense than the cold outdoor air. A column of air outside the building weighs more than a column of air inside the building, hence it tries to push in through any openings at low elevations, displacing the lighter column and pushing it up and out any openings at high elevations. The force it exerts on the indoor air is the difference in the weight of the two columns.

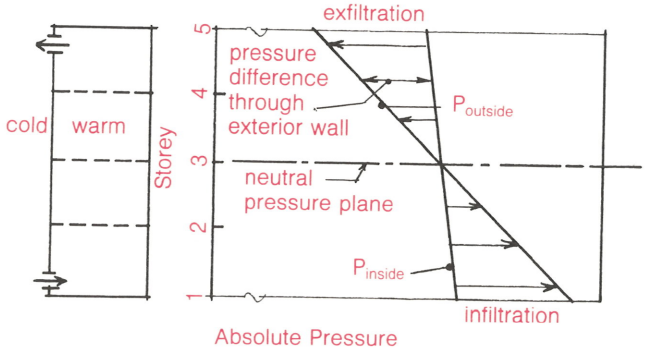
In a simplified situation where an opening exists only at the top or at the bottom of a building, Figure 2.13 A and B, the pressure indoors is respectively negative or positive over almost the full height of the building. In most buildings leakage openings will be distributed more or less over the entire height; air will flow in at the lower leaks, out at the upper ones, with an elevation in between becoming the "neutral plane" where the pressures inside and outside are equal. Figure 2.13 C illustrates this condition in a building where there is little restriction of air movement between storeys. D illustrates the more typical situation where the floors are relatively tight and vertical air movement takes place primarily in shafts (elevator, stair, duct shafts) which are separated from the storeys by shaft walls and doors which restrict but do not eliminate air movement.



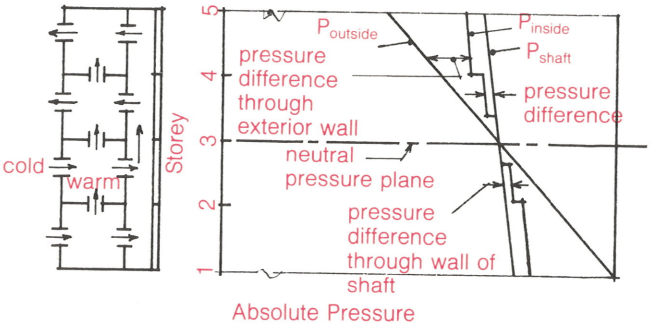
A. Air pressure inside and outside a heated building with openings at the bottom and no internal partitions



B. Air pressures inside and outside a heated building with openings at top and no internal partitions



C. Air pressures inside and outside a heated building with evenly distributed openings and no internal partitions



D. Air pressures inside and outside a building with evenly distributed openings and some internal restrictions to flow

Figure 2.13 "Stack Action" and Differential Air Pressure Across Building Envelope

In all cases the "stack action" pressure differential across the exterior walls at a given elevation is determined by the vertical distance from the neutral plane and the difference in absolute temperatures (and hence densities) between the indoor and outdoor air:

$$P_s = 3465\ h \cdot \left(\frac{1}{T_o} - \frac{1}{T_i}\right) \qquad (2.4.3)$$

where P_s is the differential pressure due to stack action (Pa) at a point,
h is the distance (m) of the point above or below the neutral plane, and
T_o and T_i are the outdoor and indoor absolute temperatures (° Kelvin)

Figure 2.14 indicates the maximum stack action differential pressures that can push inwards or outwards on building envelopes.

Where the preponderance of leaks or vents is toward the top of the building, the pressure pattern shifts toward that of Figure 2.13 B. Indoor air pressures become negative over most of the height of the building (i.e. the neutral plane shifts upward toward the roof) and the prevailing effect on the walls through the winter is infiltration. The cold outdoor air is not able to hold much moisture (even if its RH is 100% its absolute humidity is low), so no harm is done to the wall materials. Also, because the neutral plane is very close to the roof there is only a small pressure differential tending to push air through any leaks in this portion of the building envelope. Small houses with chimneys tend to operate in this mode with trouble-free walls. Large buildings with vented service shafts (or simply very leaky mechanical penthouses) also tend to operate in this forgiving fashion.

Where, however, the preponderance of leaks or vents is toward the bottom (e.g. large service entrances) or where mechanical ventilation is designed to pressurize for odour control, then the neutral plane shifts toward the ground. In this case, and in cases with mid-height neutral planes, the indoor pressure becomes positive over most of the height or at least in the upper portion of the building. Exfiltration of warm indoor air laden with water vapour in it results through any and all leaks in that portion.

Consideration of Figure 2.14 suggests that the pressure differential driving the exfiltration may well be in the range of 20 to 40 pascals in high buildings and 3 to 6 pascals in low ones, sustained throughout the heating season. Additional to that will be outward wind pressure differentials across the prevailing lee side, about 11 pascals for an

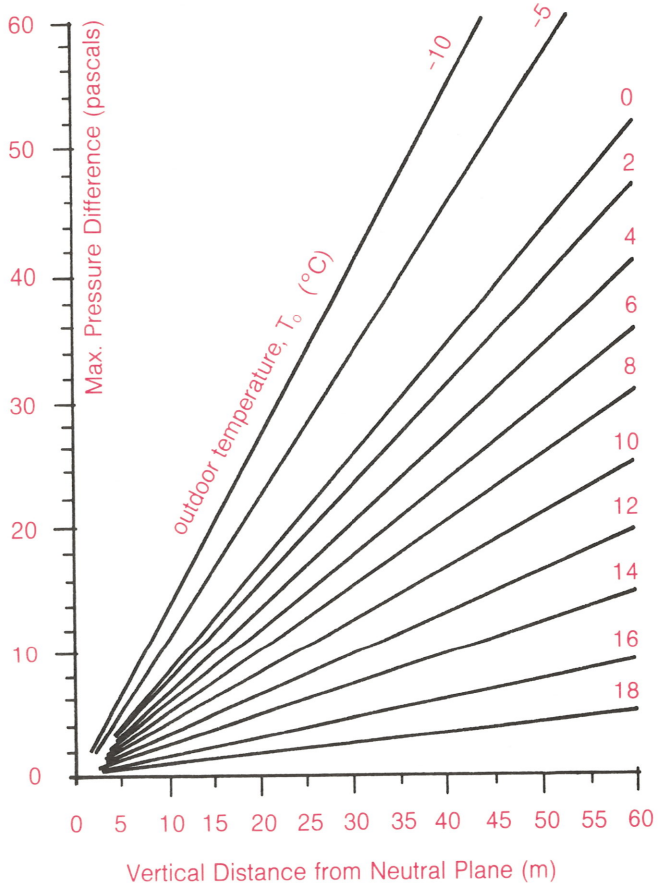


Figure 2.14 Theoretical Pressure Differential Across Building Envelope Due to Stack Action (based on 20°C indoor temperature)

average breeze of 15 km/hr. Additional again is positive pressurization by the mechanical system, which should be avoided. In sum, a range of effective "steady state" pressurization of **15** to **50** pascals should be expected in low to high buildings, at least in the upper floors, through most of the Canadian winter.

- **The leaks in the envelope:** Figure 2.15 suggests an array of leaks in a poorly sealed wall assumed to be at an elevation in the building subjected to positive indoor pressure and resulting exfiltration. The air leaks into the roof envelope will be somewhat similar, especially over partition and wall junctions into the ceiling.

Consider an area of such a wall of room size, say 5 m long by 2.4 m high. Assume that the cracks shown as ⓐ, ⓒ and ⓓ are an average of 1.5 mm in width, and that cracks similar to ⓒ or ⓓ occur also where partitions join the exterior wall. It can be seen that the total crack length can easily be 30 m, depending on the window perimeter and including an allowance for the electrical leaks, ⓑ, which certainly can not be ignored. However let us assume that the total open crack length is only 15 m.

- **Exfiltration/condensation quantities:** The ASHRAE Handbook of Fundamentals suggests that the air flow through cracks of this size can be approximated from the following equation:

$$Q = 8.6 \times 10^{-5} \Delta p^{0.65} \qquad (2.4.4)$$

where Q is the flow in m^3/s per m of crack, and
Δp is the pressure difference across the wall (Pa)

If, following our example, we assume the 15 m of crack is in a high building, Figure 2.14 suggests it would be subjected to an average outward pressure of 25 Pa for 100 days during the winter. Then the total flow of interior air out through the crack will be —

$$8.6 \times 10^{-5} \times 25^{0.65} \times 15 \times 3600 \times 24 \times 100 = 9 \times 10^4 \ m^3$$

At 20°C, the density of dry air is 1.205 kg/m^3. Therefore the mass flow is —

$$9 \times 10^4 \times 1.205 = 1.1 \times 10^5 \ kg$$

Referring to the psychrometric chart of Figure 2.11, if this air is at 35% RH, its water vapour content will be 5×10^{-3} kg/kg. Therefore this outward flow of interior air will move an amount of water vapour of —

$$1.1 \times 10^5 \times 5 \times 10^{-3} = 550 \ kg$$

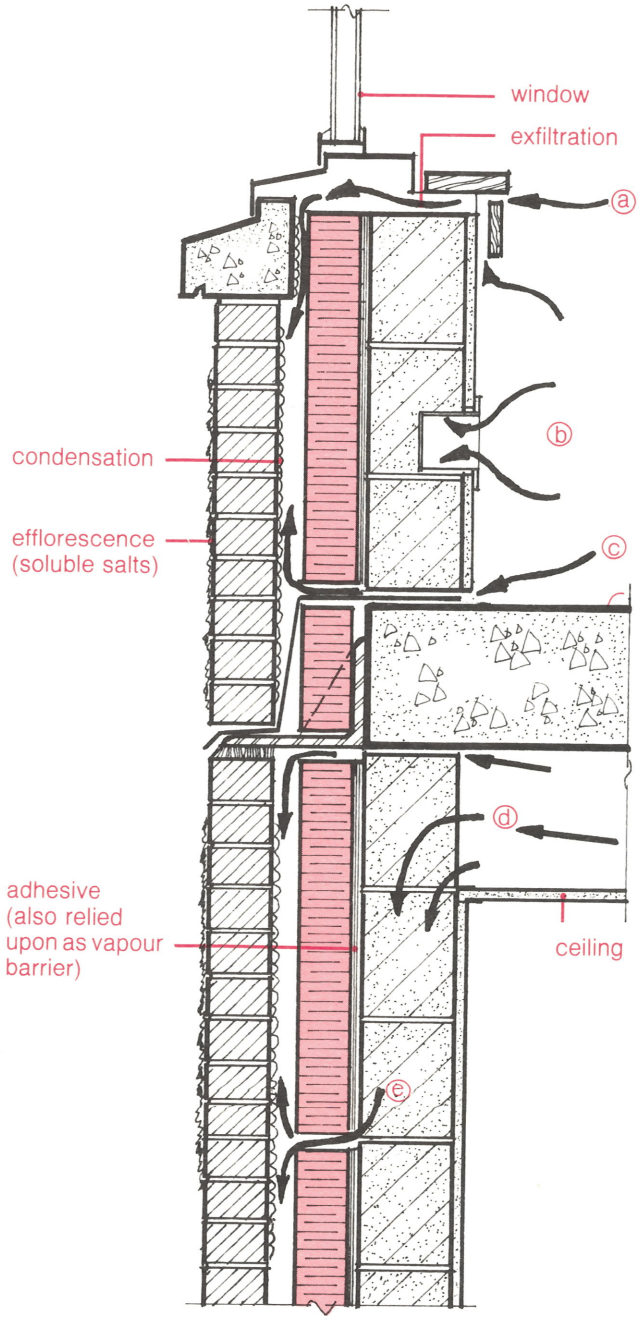


Figure 2.15 Exfiltration/Condensation Example Pattern (leakages ⓐ to ⓔ are discussed in the text)

In other words 550 kg of water vapour could move outward through the cracks in the wall of one room and virtually all of it would be deposited on or within the cold materials making up the outer portion of that wall. If the indoor relative humidity were maintained at 50% this amount would be about 800 kg. Such quantities can saturate all adjacent materials and cause efflorescence, freeze-thaw spalling, corrosion of ledgers and ties and even breakages due to the pressures exerted by the freezing of the water in confined spaces.

- **Drying factors (or lack thereof):** Figure 2.5 indicated that the air temperature in the example wall's air space is not much above outdoor temperature, therefore it can not take up much moisture in the winter. Venting of that air space to the outdoors will achieve very little sustained drying effect until the outdoor temperature becomes consistently higher in the spring. Similarly the temperature drop across the outer brick is very small in winter, as shown, so that the "vapour pressure" drop (discussed below) will be exceedingly small and can move very little water outwards by diffusion. Wind might periodically reverse the air flow with some drying effect but this is unlikely to balance the wetting effect of the constant outward tendency due to stack effect, which acts 24 hours a day during cold weather. In sum, it must be assumed, just slightly conservatively, that all the winter condensation accumulates in the envelope at least until the outer materials become saturated. After that, the excess condensate will run down and should be led outdoors through drains. Ventilation of the outer materials and/or their ability to breathe, as in the case of highly permeable materials, can not be counted upon to help avoid saturation due to exfiltration/condensation during the winter, although these measures or qualities can be useful in allowing faster drying in the spring.

The corrective: the complete air barrier (and vapour barrier): Clearly it has become critically important to airtighten insulated building envelopes where the indoor RH is appreciable. Fortunately masonry/concrete buildings are generally amenable to practicable and inspectable airtightening. In most circumstances, the air/vapour barrier must be toward the warm side, (i.e. located inward from dew point) and must be complete over the entire building envelope surface. Where the floors and crosswalls are of solid concrete it is only necessary to seal the air/vapour barrier to them where they intrude into the envelope; they themselves do not constitute air paths.

In the example of Figure 2.15 the insulation location and material (cellular polystyrene) presents one plane that can be completed as an effective air/vapour barrier. The insulation must be installed with fully "buttered" joints on a full bed of adhesive

which is spread on the outer surface of the inner wythe and on the sides of the intruding concrete floors and cross-walls. However it is often difficult to make this complete and sound, working in outdoor conditions, and it does not remain inspectable and repairable.

For such reasons it is strongly recommended that the final visible interior surface — the interior finish in most cases — be installed and treated as the primary air/vapour barrier. For example, the leaks ⓓ in Figure 2.15 can be stopped by continuing the finish up to meet the concrete floor and caulking or taping the junction; leak ⓒ can be stopped by caulking or taping the finish to the floor surface. The usual electrical box leaks ⓑ can be restricted by means of special boxes and/or gaskets now available or by eliminating such boxes on exterior walls. The usual gaps ⓐ can be sealed with caulking before the finish trim is applied. Almost all critical points are visible; all are accessible for repairs; the intruding floors and crosswalls conceal no leakage paths within.

Where hollow partitions such as steel stud or hollow core unit masonry constructions intersect the exterior envelope, the latter's interior finish should first be made continuous. Where construction sequences do not allow that, then polyethylene film, at least 0.15 mm thick, should be installed first across these junctions. In fact, where frame partitions, columns, ductwork, chases or other paths or complications abut or intrude into the envelope, it can be advantageous to use large-sheet polyethylene film for the whole air/vapour barrier job. Figure 2.16 suggests the approaches to sealing the film well enough to avoid excessive exfiltration/condensation.

Controlling vapour diffusion: Water vapour enters building envelopes from indoors not only as a part of moving streams of air, but also by itself as an independent gas diffusing through building materials. This mechanism has been recognized since the 1930's; hence the emphasis on **vapour** barriers in virtually every publication on building practice since that time. It is only in recent decades that we have realized that vapour diffusion can transfer only a very small fraction of the quantities of water moved via air leaks and that most condensation related envelope problems are caused by exfiltration. The dominant emphasis is now correctly directed to installation of the vapour barrier in such a way as to also create a high integrity air barrier as just discussed. Nevertheless there are constructions where it may be desirable to restrict condensation to very small amounts, or try to avoid it altogether — such as sandwich panel constructions which may have no air leaks through themselves but also have no air space which can ensure venting and drying out in summer. Controlling vapour diffusion must be given consideration.

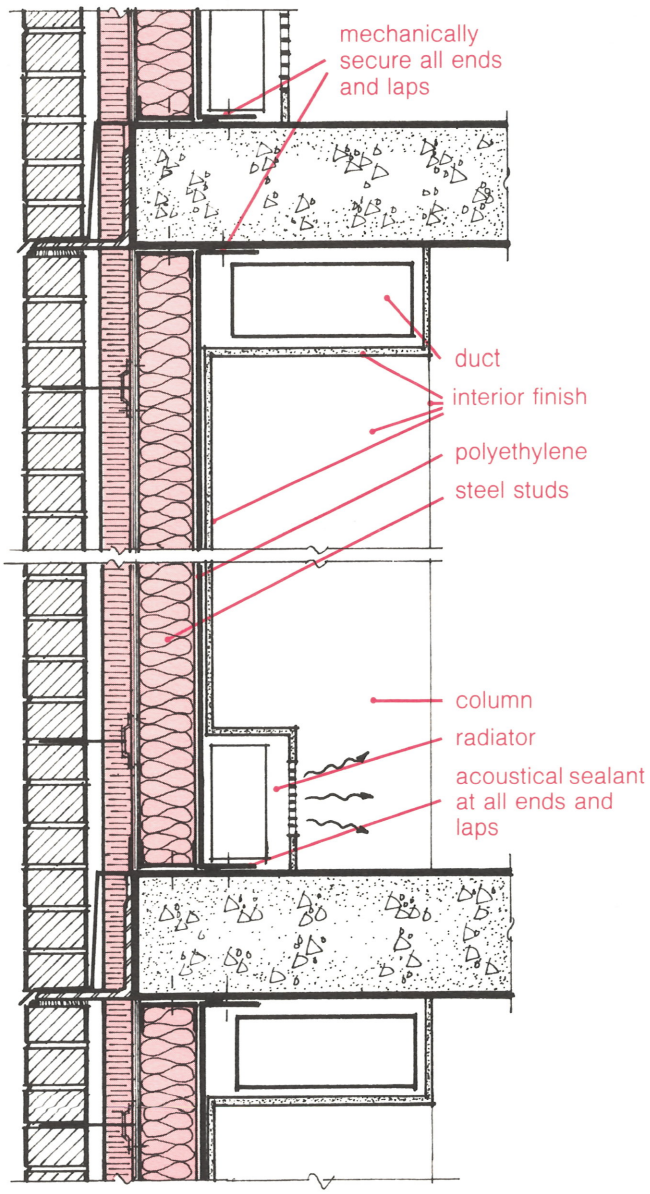


Figure 2.16 Polyethylene Film Used as Air/Vapour Barrier

The gas, water vapour, exerts its own pressure, water vapour pressure, which is independent of the air pressure but is dependent on the air temperature and relative humidity. The vapour pressure in air at 100% RH is called the saturation vapour pressure and is different for different temperatures. It can be found on the psychrometric chart (Figure 2.11) by reading on the vapour pressure scale opposite the temperature on the saturation curve. The vapour pressure in air at any other relative humidity is determined by multiplying the saturation vapour pressure by the relative humidity.

e.g. Saturation vapour pressure at 20°C,
P_s = 2.3 kPa
Vapour pressure at 35% RH and 20°C,
P = 2.3 × 0.35 = 0.81 kPa

Where the vapour pressure is different on the two sides of a building component, as will be the case when the air temperatures and/or relative humidities are different, water vapour will be forced through that component. The flow can be determined from the following equation:

$$V = \frac{A \bullet \Delta p}{R_v} \qquad (2.4.5)$$

where V is the vapour flow in nanograms per second, ng/s (10^{-9} g/s),
A is the area through which the flow occurs (m^2),
Δp is the vapour pressure difference (Pa), and
R_v is the total resistance to vapour flow of the component (Pa•s•m^2/ng)

The resistance to vapour flow of various materials is given in Appendix A. Like thermal resistances, these resistances are proportional to thickness for a homogenous component and can be added together for a multi-component assembly.

The above equation is only applicable in calculating vapour flow through a multi-component assembly if condensation does not occur within the assembly. Condensation occurs if the vapour pressure at any point due to vapour flow through the assembly exceeds the saturation vapour pressure consistent with the temperature at that point. The procedure for determining if this will occur is outlined below and is illustrated in Figure 2.18 using the insulated cavity wall used in previous examples:

1. The temperature profile is plotted as was done in Subsection 2.2.3 but assuming some average long term outside temperature.

2. The saturation vapour pressure (P_s) profile resulting from the temperature profile is plotted.

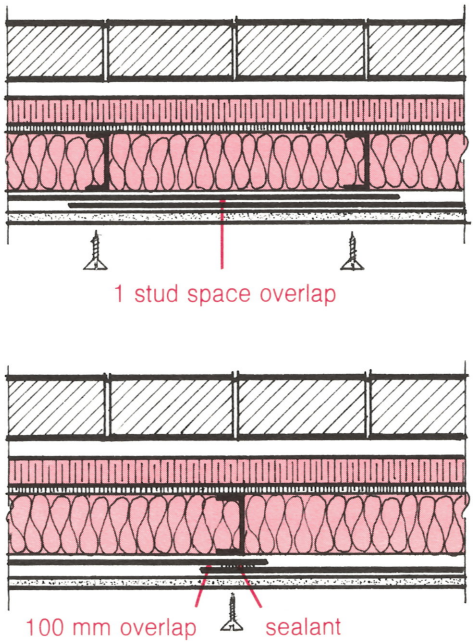


Figure 2.17 Recommended Joints in Polyethelene Air/ Vapour Barrier

3. The vapour pressure profile consistent with uniform vapour flow through the whole assembly (P_u) is plotted. This is done by first determining the inside and outside vapour pressure and dividing the total pressure drop in proportion to the vapour resistances of the individual components.

4. If P_u exceeds P_s at any point, it can be assumed that condensation will occur at the next outward interface between two components and that that point will be at saturation vapour pressure. The total vapour flow into the wall is calculated using Equation 2.3.5 with Δp equal to the difference between the interior vapour pressure and the saturation vapour pressure at the condensation plane and R_v equal to the total vapour resistance between the interior and the condensation plane. The total vapour flow out of the wall is calculated using Equation 2.3.5 with Δp equal to the difference between the outside vapour pressure and the saturation vapour pressure at the condensation plane and R_v equal to the total vapour resistance between the condensation plane and the outside. The difference between these two flows is the rate at which water condenses at the condensation plane.

5. If P_u does not exceed P_s at any point, the Equation 2.3.5 can be used directly to calculate vapour flow through the whole wall.

The wall in Case I, Figure 2.18, is identical to that in the exfiltration/condensation example of Subsection 2.3.2. As the saturation vapour pressure is not exceeded at any point Equation 2.3.5 can be used directly to calculate vapour flow as follows:

$$A = 5 \times 2.4 = 12 \text{ m}^2$$

$$\Delta p = 700 - 500 = 200 \text{ Pa}$$

$$R_v = 5.88 \times 10^{-2} \text{ Pa•s•m}^2\text{/ng}$$

$$V = \frac{12 \times 200}{5.88 \times 10^{-2}} = 4.08 \times 10^4 \text{ng/s}$$

Flow over
100 days $= 4.08 \times 10^4 \times 10^{-12} \times 3600 \times 24 \times 100$
$= 0.35$ kg

In Case II, Figure 2.18, the interior humidity has been increased and a more permeable insulation used. This results in the saturation vapour pressure being exceeded within the insulation. Assuming condensation takes place on the inner surface of the outer wythe, the vapour flow is calculated as follows:

$$A = 12 \text{ m}^2$$

$$\Delta p = 900 - 650 = 250 \text{ Pa}$$

$$R_v = 8.07 \times 10^{-3} \text{ Pa•s•m}^2\text{•/ng}$$

$$V = \frac{12 \times 250}{8.07 \times 10^{-3}} = 3.72 \times 10^5 \text{ ng/s}$$

Flow over
100 days $= 3.72 \times 10^5 \times 10^{-12} \times 3600 \times 24 \times 100$
$= 3.2$ kg

Comparing these figures with the 550 kg which the calculations in Subsection 2.3.2 indicated could be moved through this same wall by air exfiltration, it is apparent that air exfiltration is a more serious threat by far to the integrity of the building envelope than is vapour diffusion. The principle is clear: the air/vapour barrier must first be chosen and executed as a reasonably complete air barrier. In most, but not all cases, the interior finish will provide adequate resistance to vapour diffusion. Even where this is not the case or where it is desirable to eliminate completely the possibility of diffusion/condensation, the vapour resistance of the interior finish can easily be improved. This is demonstrated in Case III, Figure 2.19, in which two coats of enamel paint are added to the wall in Case II and the saturation vapour pressure is not exceeded within the wall.

Summary of Air/Vapour Barrier Recommendations

Wherever possible the final interior surface should be installed and finished in a manner that will allow it to act as a barrier to both air movement and vapour diffusion. This involves the following design and installation steps:

— avoidance of concealed passages which communicate between the interior and the outer portions of the building envelope or ensuring that the interior finish is continuous through or past such concealed spaces (e.g. continuing the wall finish up past a suspended ceiling or behind radiators)

— sealing joints in the interior finish

— minimizing such joints

— sealing the junctions between the interior finish and any interruptions of it such as at cross walls, columns, floor and roof slabs, windows and doors, electrical outlets, etc.

— minimizing such interruptions

— painting or otherwise sealing the interior surface as necessary to provide the required vapour resistance.

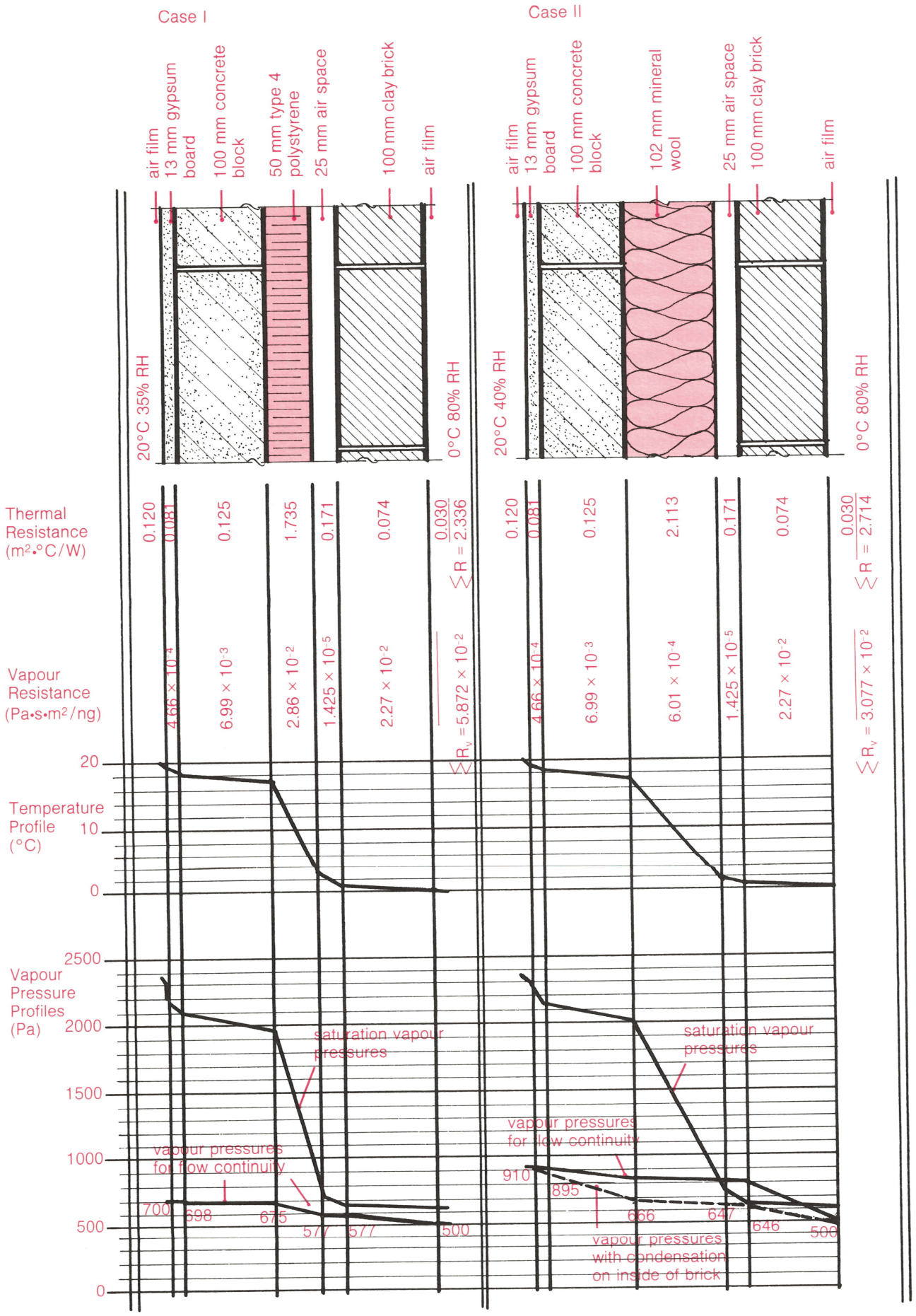


Figure 2.18 Vapour Pressure Profiles

Where, due to the number of unavoidable interruptions of the interior finish, it is impractical to use it as the air/vapour barrier, a separate barrier of polyethylene sheet at least 0.15 mm thick should be installed. It should be installed:

— as close to the warm side of the insulation as possible,

— in as large sheets with as few joints as possible,

— with the joints solidly backed, generously overlapped and sealed,

— continuously past columns, partitions, radiators, etc. or, failing that, sealed to such interruptions.

The point to bear in mind is that the prime objective is to stop the movement of air through the envelope.

2.5 Rain Penetration

The envelope's function of protecting against rain is not unique to energy-conserving buildings, but the presence of thicker insulations creates conditions in the outer wall materials which are less favourable to drying out as has been shown. The importance of limiting the entry of water and of venting the outer materials is therefore increased.

The main forces of gravity and wind pressure, augmented by capillary forces in many cases, try to push rain through the building envelope. The roof of course contends primarily with gravity; the walls primarily with wind pressure.

2.5.1 Roofs

Roofs in Canada are subjected to extreme conditions, which is reflected in the frequency with which roof problems occur. The defensive tactics for roofs should always include working with gravity: sloping to drains rather than relying on dead flat roofs with their attendant ice expansion and exposure problems.

The present trend toward incorporating the complete drainage membrane under the insulation, thus protecting it from the surface extremes of temperature changes and ultraviolet attack, is strongly recommended. This "protected membrane roof" utilizes the surface of the insulation itself to shed most of the rain, while the warm, fully protected membrane under the insulation drains off the remainder that percolates down to it. This "two-stage" roof approach becomes somewhat more difficult in practice as the insulation becomes thicker: the buoyancy or flotation forces lifting the insulation can become great.

A problem often associated with conventionally insulated roofs is related to the fact that some types of rigid insulation have rather high coefficients of thermal expansion. If they are installed in cold weather with no gaps between the individual sheets, expansion in warm weather may cause ridging at the joints with resulting stress and possible tearing of the roof membrane if it is installed conventionally on top of the insulation. Conversely if the insulation is installed in warm weather, contraction in cold weather may also cause tearing of the membrane unless precautions are taken to creat a slip plane between the insulation and the membrane. Both these problems are avoided with the protected membrane approach.

In summary, then, the protected membrane roof is the recommended approach.

2.5.2 Exterior Walls

The "two-stage" approach was used to control rain penetration of walls long before it was used with roofs. The traditional layered, veneered and cavity constructions are examples of the two stage concept which were adopted particularly for regions of severe, sustained wind-driven rains and then for high-rise exposures in general.

Later the same thinking carried over for "through-wall" joints for such exposures. Notable examples are the two-stage joint detailings of precast sandwich panel walls and the through-wall joint details between windows and surrounding walls of all types of construction.

In using the earlier two-stage approach to the whole wall or through-wall joint, the designer attempts to stop both wind and rain at a rather watertight, airtight outer surface. The probability of some water entry is recognized and accommodated by providing a clean cavity or gap in the wall (or the joint) behind the outer surface, with a second air barrier wall (or joint seal) on the inner side of the cavity. Water leaks driven through the inevitable flaws in the outer surface are drained through the cavity or gap and led back outdoors at flashings and small drain openings below.

The difficulty with this approach is that the outer surface is usually almost, but not quite, air- and watertight. When it is subjected to a wind pressure it isolates the cavity from this pressure sufficiently to create a pressure drop; i.e. the cavity will be at a lower pressure than the outer face of the outer surface. However it is likely to be at a higher pressure than the interior of the building. During a rain storm the outer surface will be covered with a film of water. In calm conditions this film might bridge across the

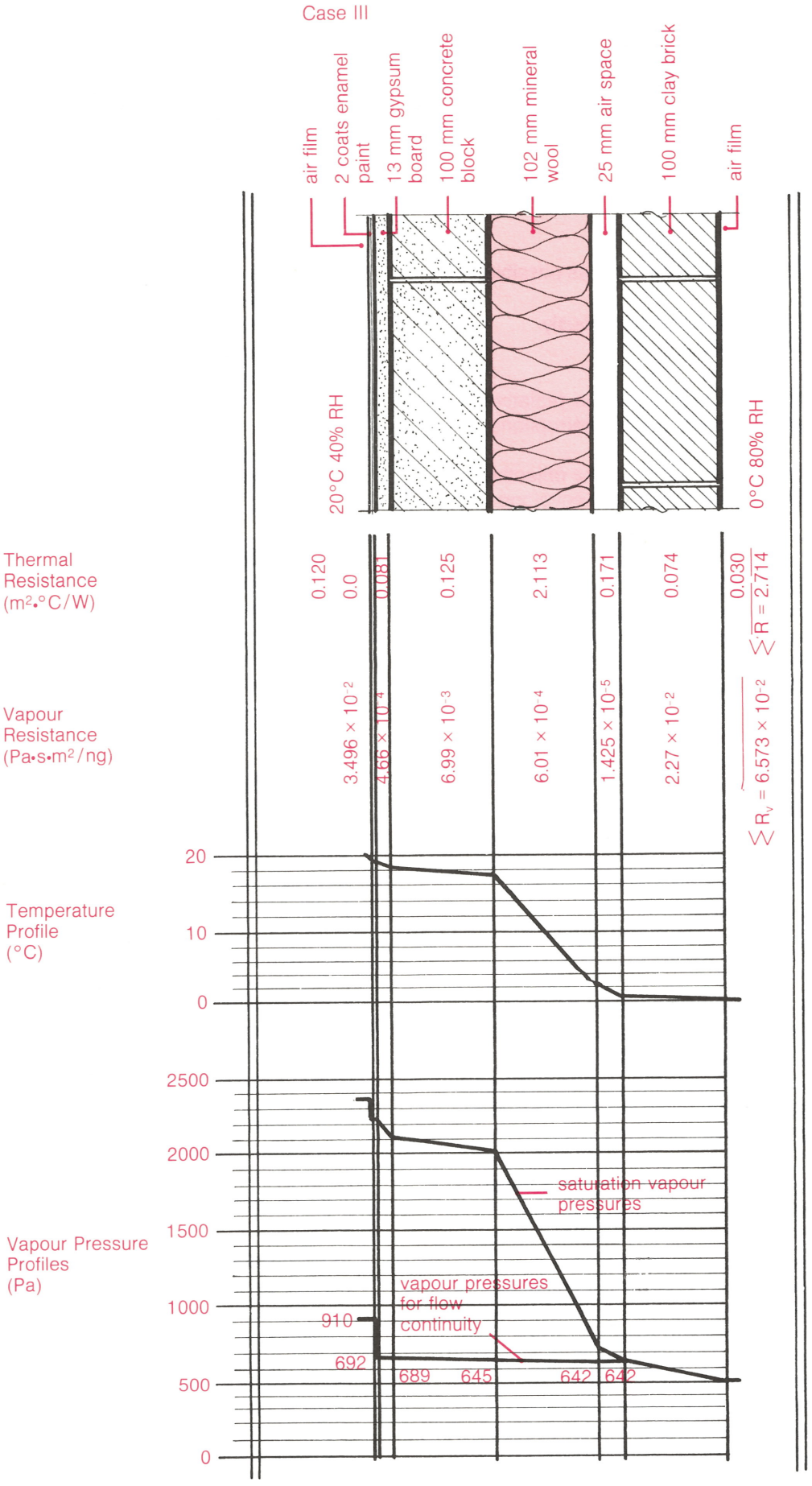


Figure 2.19 Added Vapour Resistance Due to Paint

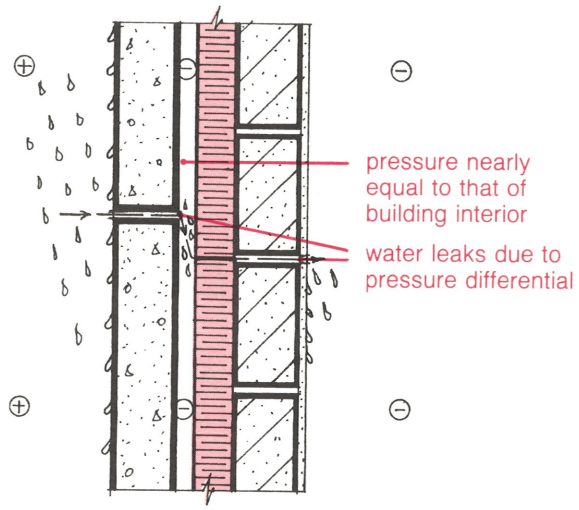
flaws in the surface; but, in wind conditions, the pressure drop drives the water through the flaws. The water can jet across the cavity with considerable force, wetting the inner wall or joint seals, and then be driven through the inner wall or joint seals by the remaining pressure differential.

Recognizing this failing of traditional two-stage walls and joints, building scientists have taken the concept a simple step further. The outer wall surface is intentionally vented so that the pressure in the inner cavity or gap is essentially equalized with the wind pressure; thus the wind pressure bears almost entirely against the inner wall or seals. Since very little pressure differential exists between the vented outer surface and the cavity there is little force or air stream velocity to push or carry the rain through. The outer surface acts as a rain screen; the arrangement becomes a rain screen wall or rain screen joint as illustrated in Figures 2.20B and 2.21. It is no longer necessary to achieve a perfectly sealed inner wall (or joint) since it is unlikely to be subjected to significant amounts of water. However **perfection** should continue to be sought in order that an **adequately** sealed inner wall will be achieved.

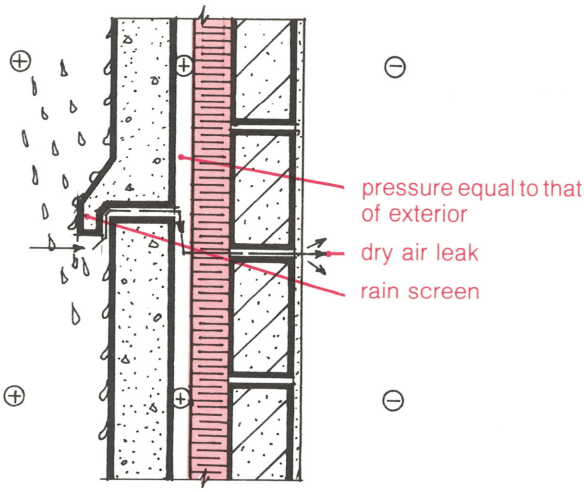
In Figures 2.20 and 2.21 positive (inward) pressures are depicted as + and negative (outward) pressures as −.

The "rain screen" effect has existed for ages; such traditionally reliable constructions as clay weather-tile, wood shingles and even thatched roofs are all vented two-stage "rain screen" assemblies. The Scandinavians must be credited for the formal recognition, development and application of the concept in recent times and for the design and deployment of rain-screen-based window details, cladding, curtain wall, masonry and precast details, that work well anywhere. The Division of Building Research of the National Research Council of Canada has documented and promulgated the approach in North America. It is now used routinely by industry as exemplified by the fully drained/vented cavity or veneer constructions and the drained/vented through-wall joints as in Figures 2.21A and B. In all cases the rain impinging directly into such vents is of minor importance; the vents are sloped outward and protected by drip edges to avoid blockage by unbroken rain films. The essence of the concept and the practice is to avoid a sustained pressure drop across the rain film flooding the outer surface.

In some circumstances the rain screen approach can be rendered less effective by extreme pressure variations or reversals. This can happen especially at building corners as shown in Figure 2.22A unless the cavity is blocked at such corners as in Figure 2.22B (using closed-cell insulations that neither absorb water nor constitute a thermal bridge).



A. Large Plain Wall: unvented cavity does not act as a complete drain; outer wall is not a rain screen.



B. Large Plain Wall: rain screen works despite leaks in air barrier.

Figure 2.20 Dealing with Wind-Driven Rain: Large Plain Wall

It has not yet been possible to use theory or testing to quantify or allow calculation of the rain screen relationships such as vent sizes, spacing, cavity or air space or joint space size. Designers and component manufacturers have used judgement and experience with success. For example, the vents of precast sandwich panels as indicated in Figure 2.21 are usually of 6 mm internal diameter and are spaced about 3 m apart in inland locations generally and 2 m apart in coastal areas or in very high buildings.

Finally, recalling the internal source moisture problems discussed in Subsection 2.3, it is clear that the loose outer skin nature of rain-screen design is also ideal for discouraging the accumulation of moisture from both exfiltration and vapour diffusion from indoors. The water vapour is encouraged to escape before completely condensing, or at least is drained away or evaporated more quickly and harmlessly in mild periods. The details recommended in Section 4 utilize the rain screen two-stage approach wherever practicable.

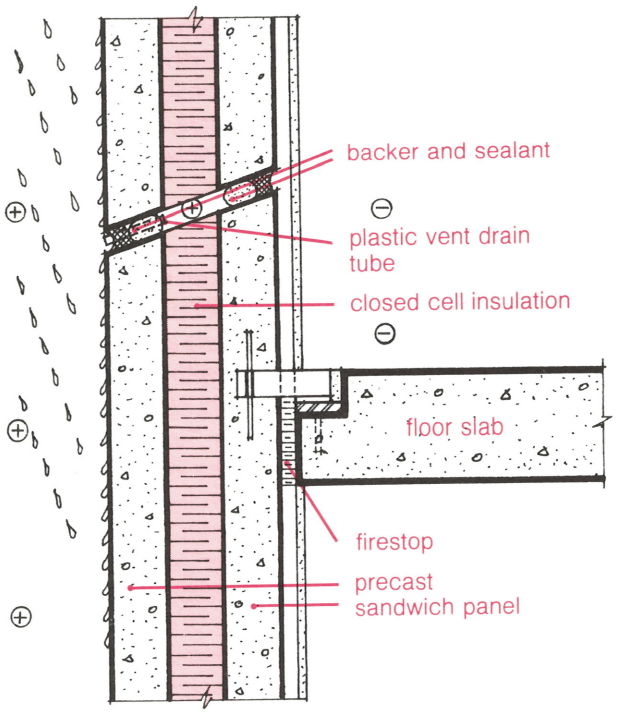
2.6 Fenestration

Fenestration is a term used for any light transmitting opening in a building wall, floor or roof. Windows are the most important form of fenestration which designers must consider. Building Codes prescribe the provision of certain minimum areas of windows for residential occupancies.

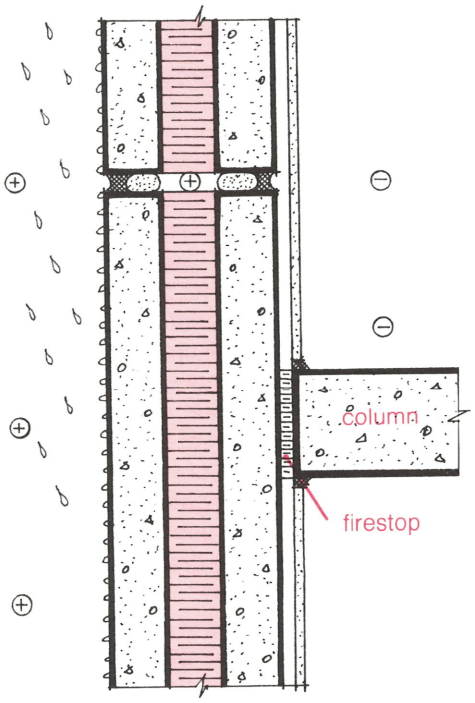
Windows play a very important role in the design of buildings for energy efficiency. Even the best sealed window units employing multiple layers of glazing have a much lower thermal resistance than that provided by insulated wall assemblies. Thus, regulatory documents for energy conservation may place restrictions on the amount of glass area which may be provided. Windows are, however, an important source of heat gain through solar effects and if properly oriented can play a significant role in energy conservation when thermal storage effects are utilized.

The provision of proper shading devices to enable the utilization of solar radiation effects for heating, without requiring excessive cooling during summer or discomfort in those buildings which are not cooled is an important consideration. Concrete construction is ideally suited to the provision of exterior shading by roof overhangs, balconies and window overhangs or eyebrows.

Detailed information on window assemblies and on the proper orientation, sizing, location and shading of windows is available in thermal design texts, such as the Energy Conservation Design Resource Handbook (5), Walls, Windows and Roofs for the



A. Horizontal joint with outer vent-drain



B. Vertical joint vented via the horizontal joint

Figure 2.21 Two-Stage Through-Wall Joint Vented to Function as Rain Screen.

Canadian Climate (1) and, for housing and small buildings, in the Builders' Guide to Energy Efficiency in New Housing (6).

Appendix C of this Guide contains information which illustrates the use of some of the provisions contained in the Measures for Energy Conservation in New Buildings (7) which concern window orientation and shading.

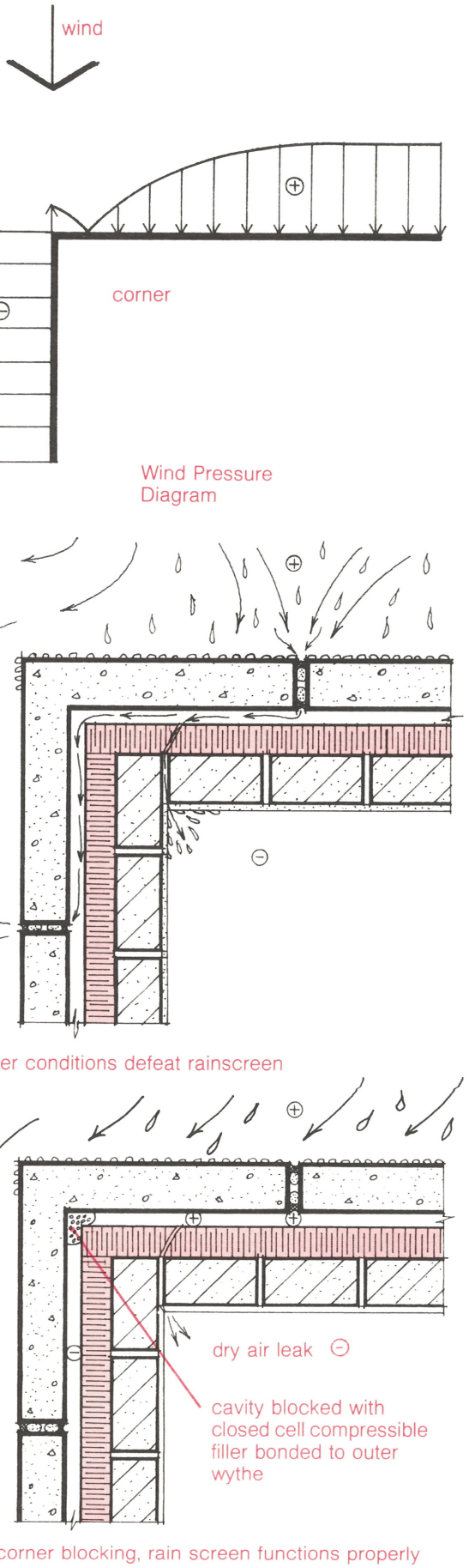

wind
corner
Wind Pressure Diagram
A. Corner conditions defeat rainscreen
dry air leak
cavity blocked with closed cell compressible filler bonded to outer wythe
B. With corner blocking, rain screen functions properly

Figure 2.22 Dealing with Wind-Driven Rain at Corners.

2.7 References

1. Walls, Windows and Roofs for the Canadian Climate
   — J.K. Latta
   Division of Building Research,
   National Research Council of Canada,
   1973

2. Handbook and Product Directory, 1977 Fundamentals
   — American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc.

3. Studies on Exterior Wall Air Tightness and Air Infiltration of Tall Buildings
   — G.T. Tamura and C.Y. Shaw
   Division of Building Research,
   National Research Council of Canada
   DBR Paper No. 706
   1976

4. Predicting Air Leakage for Building Design
   — G.T. Tamura
   Division of Building Research,
   National Research Council of Canada,
   Technical Paper No. 437
   1974

5. Energy Conservation Design Resource Handbook
   — The Royal Architectural Institute of Canada
   1979

6. Builders' Guide to Energy Efficiency in New Housing
   — Housing and Urban Development Association of Canada
   and the
   Ontario Ministry of Energy
   1980

7. Measures for Energy Conservation in New Buildings, 1978
   — Associate Committee on the National Building Code, National Research Council of Canada

SECTION 3
THE EFFECT OF BUILDING MASS

Throughout their lifetimes, most buildings are required to provide space at a near uniform temperature, regardless of fluctuations and extremes of the exterior climate, and regardless of the various activities and uses of the interior space. Until recently, the task of achieving a near constant interior temperature in a building was left to the mechanical systems: temperature drops were met directly with purchased heat, and temperature rises were countered through venting or mechanical cooling where available. There is a growing awareness among building designers that considerable building mass is an asset in terms of achieving that objective of interior temperature uniformity. Heat sources causing troublesome fluctuations in interior temperatures can be used to advantage in a "passive" fashion by mass, and turned into energy savings in most buildings in the winter, and in cooled buildings in the summer.

Today more than ever, the importance of structural mass is being recognized: the more buildings are insulated, the greater is the importance of fluctuating solar and internal gains within the energy budgets of buildings. As a result, the use of the thermal properties of structural mass should not be overlooked in the design of our new generation of energy efficient buildings.

The basic principles of energy saving with structural mass are discussed in the following sections, with emphasis on design considerations that will improve the opportunities for energy conservation with mass.

Recommendations

- Wherever possible, insulation should be placed outside the mass of the structure or sandwiched between mass layers so that part or all of the mass in the structure will be coupled with solar and internal heat gains. (Subsection 3.1)

- In buildings with relatively high ratios of solar and/or internal gains to heat losses (office buildings, apartments, passive solar houses, "superinsulated" houses, etc.) efforts should be made to make best use of the available mass in the structure inside the insulation layer by —

  — reducing the thermal resistance between the inside air and the structure (e.g. exposed uncarpeted floors, hollow core slabs) and by
  — improving air circulation and bringing the interior air into contact with as much structural mass as possible (Subsection 3.2; 3.2.2)

- Heating and cooling (if any) thermostats should be set with as broad a temperature band in between them as possible. Low temperature setting for heating; high temperature setting for cooling. This gives internal mass a chance to do its work and saves energy directly. (Subsection 3.2.4; 3.3)

- In buildings with low ratios of internal gains to heat losses (houses, warehouses) and with potentially large amounts of available interior mass (e.g. concrete and masonry structures with insulation placed towards the outside) the south-facing window area should be large and the structural mass should be used to store the excess heat produced (passive solar design). (Subsection 3.2.6; 3.4)

- In large office buildings the mass in the structure should be taken fully into account in sizing heating and cooling plants. There is potentially a direct saving in plant investment, and an indirect saving in cooling energy annually. (Subsection 3.2.5; 3.3)

- The reduction in insulated thickness allowed for heavy construction in codes should be investigated. The allowance may be significant in dollar terms if the next step in insulation level required to meet the codes is difficult and costly to achieve. (Appendix B)

3.1 External Mass and Energy Conservation

Solar heat gains on the exterior portion of walls and roofs reduce the heating requirements of a building during the heating season by counteracting heat flow from the warm inside to the cold atmosphere. In certain circumstances, the flow of heat may actually be reversed.

In **warmer** climates and for certain types of buildings and locations, the winter time solar gains through the walls and roofs may be so high that no heat at all is required during peak sun hours and venting or cooling may be needed to maintain comfortable conditions inside. Such a phenomenon can be quite common since solar gains through the structure and windows, as well as gains generated from equipment, appliances and people often tend to peak at about the same time of day.

In the case of heavy construction (solid masonry, concrete. . .) the solar gains accumulated through the walls and roof will only affect the internal space hours after the peak sun hours (the lag effect of massive construction) when there may be no surplus of internal gains and when a lighter building would require some space heating. The lag effect spreads the free heating energy over time, thus reducing the peaking of indoor temperatures during the day and forestalling the need for heating later in the evening. This is the way heavy construction in walls and roofs saves energy and improves comfort in moderate climates.

In **colder** climates, such as encountered across most of Canada, the opportunities for saving heat energy with mass shift from the exterior structure of the building to the interior. Insulation of the outer structure of buildings has the primary purpose of reducing the potentially high heat loss. However, the insulation also reduces solar gains through the opaque portions of the structure in the same proportion as the heat loss reduction (a positive effect in the summer but not in the winter). Mass on the exterior of the insulation layer has less of a role to play. The internal gains, however, remain the same with added insulation. These are gains from equipment, appliances, people and solar gains through windows. On a relative basis therefore, the internal and "window-solar" gains become more significant and contribute to a greater extent to potential heat surplus, which is the indicator of an opportunity for saving heat with mass.

Thus, in colder climates, the most effective use of thermal mass to moderate interior temperature swings and save energy in **insulated** structures occurs when the mass is placed **inside** the insulation where it will be in contact with that greater quantity of

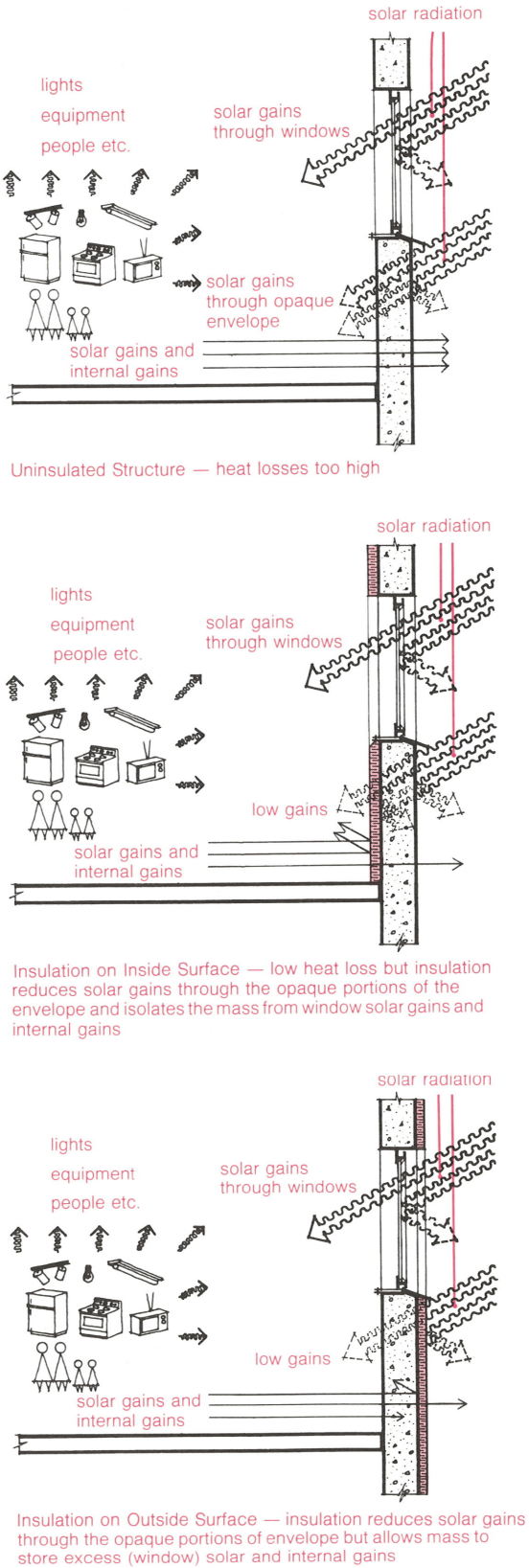


Figure 3.1 The Effect of Insulation and its Location in the Role of Mass.

surplus free heat. These considerations are illustrated in Figure 3.1.

It is this approach to energy saving with mass that is discussed in the following subsection.

NOTE: The property of specific heat capacity of a material does not "interfere" with other properties of the material: e.g. thermal conductivity and absorptivity of solar radiation. Additional heat capacity does not resist heat flow, and it can not induce more absorption of solar radiation. Therefore, for a given set of conditions (interior and exterior temperatures, solar radiation, thermal conductivity of the materials, surface absorptivity and surface film heat transfer coefficients) the gross heat gains and heat losses through the structure over a period of time (say one week) will be unchanged by the presence of more or less mass in the structure. Since mass can neither create nor destroy energy, the heat energy that is saved with additional mass is energy that is available in a less massive structure but could not be used or stored at the time it was available, and would have been vented, cooled or simply lost to the outdoors as indoor temperatures increased. Heat energy saved by mass is essentially stored energy that would have been **surplus** free heat in a lighter structure. Storing heat that is not surplus does not represent a potential for heat saving.

3.2 Storage of "Free Heat" in Internal Mass

3.2.1 Basic Principles

There are many factors that affect the heating energy balance of a building at any point in time, as illustrated in Figure 3.2:

- heat loss through the envelope
- heat loss through ventilation/air leakage
- heat gains from appliances, equipment, people, lights, etc.
- heat gains from the sun through windows
- heat gains from the sun through the opaque portion of the envelope
- heat stored previously in the mass of the exterior and interior structures
- air circulation within the structure
- heating and conditioning control system (thermostat setting schedules)

These factors combine to make up the energy balance of a building in the following fashion: all the gross heat losses and heat gains can be added and the difference between losses and gains determines the amount of purchased heat required. (Figure 3.3A)

Over the course of a day during the heating season, there may be more gains than losses at some periods resulting in a surplus of free heat. (Figure 3.3B)

This heat must either be vented, removed by cooling, or stored to prevent overheating of the interior air. Venting in the winter time is a waste of valuable energy, and cooling to remove surplus heat is even more wasteful at a cost of more energy. Storing this heat can be particularly useful as these periods of surplus (coinciding periods of high solar gains and internal gains) can be followed by periods of low free heat in the evening or night, for many types of buildings and occupancies. Stored free heat can displace purchased energy later in the day or evening, thus resulting in a net saving of purchased energy. (Figure 3.3C)

The above discussion illustrates the simple concept of heat saving with mass. In fact the mechanisms are more complicated.

Like any storage system there must be a means of transferring the surplus heat to the mass, and later a means of transferring heat from the mass to the areas where heat is needed. However, in a building, there are many sources of heat to contend with, and there is no control system to regulate the storing and releasing process. The process of storing heat in and releasing heat from the building's mass is more or less automatic. Large increases in interior free heat cause local temperatures to rise and heat will flow to mass in quantities that depend on the thermal coupling between heat source and mass and the capacity of the mass to store that heat. As heat is needed later on, air temperatures drop and heat stored in the structural mass is available to supply the heating. That heat is used instead of purchased heat supplied by the heating system.

As this process uses the building's inherent mass there is no additional capital cost attributable to it nor is there any on-going day-to-day operating cost or attention required. The mass effect is a bonus that can increase with heavier construction materials. On the other hand, the mechanisms just described (air temperature swings, thermal coupling to mass) are not normal design considerations and can easily be overlooked or interfered with in the course of building design and operation.

For instance, the same factors that drive the storage/release cycle (i.e. inside air temperature swings and air circulation) are also controlled by the heating/cooling and air handling systems. The heating and cooling control systems are often designed or operated to eliminate heat surplus immediately as it occurs (e.g. air return inlets located in light fixtures), at a cost of more energy, while leaving no role for the mass to play in the process.

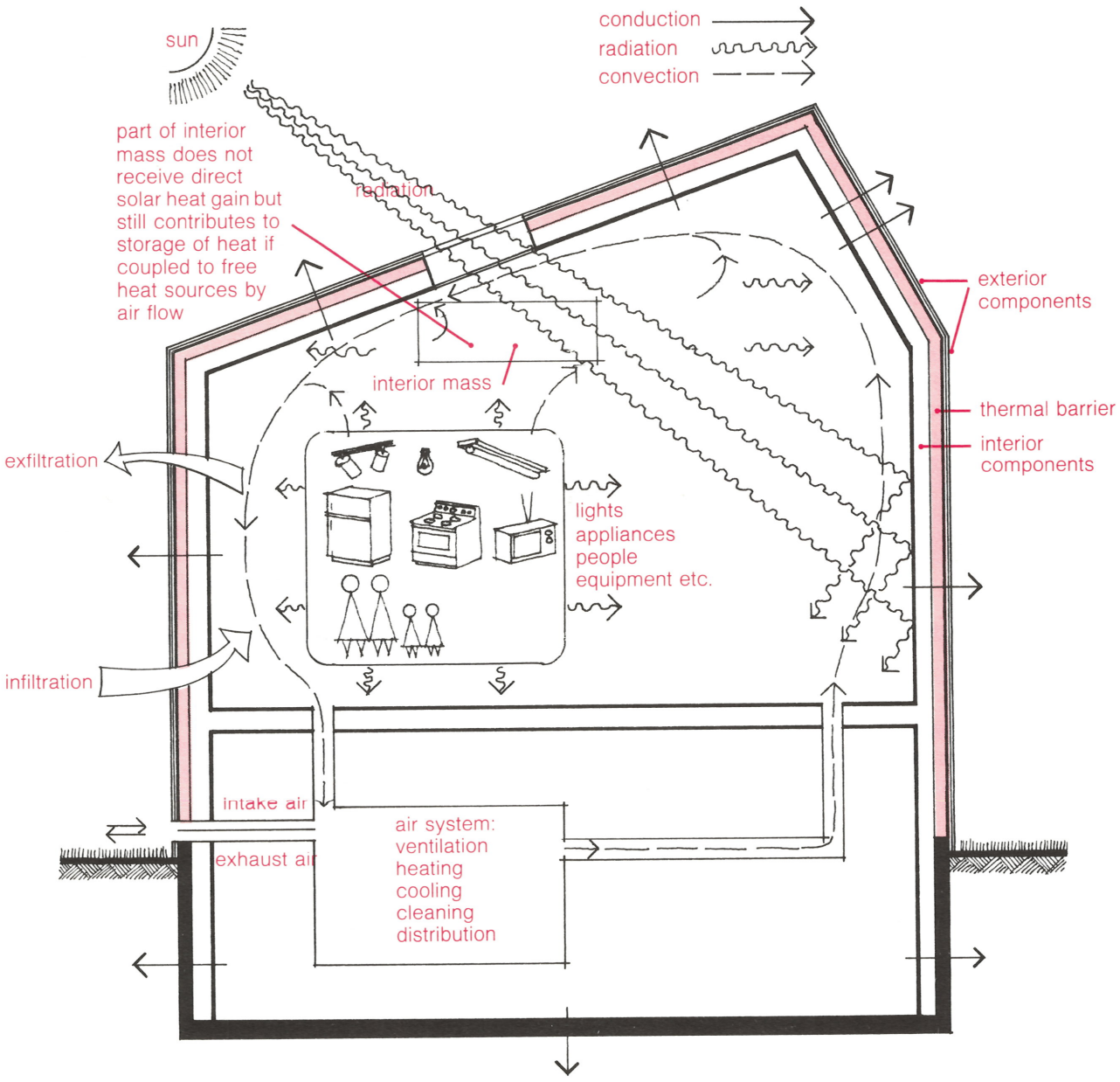


Figure 3.2 Storage of Free Heat in Internal Mass.

Therefore, saving heat energy with mass can be viewed as a bonus, but there are many factors that can improve that bonus and that should be considered at the design stage.

These design considerations fall into two categories. Those that define the **opportunity** for saving and those related to the **effectiveness** of mass in its energy saving role:

Factors Defining the Opportunity
- — solar gains through windows
- — internal heat gains
- — insulation levels (R values of the envelope)
- — ventilation rates

Factors Defining the Effectiveness
- — amount, heat capacity and location of building mass
- — thermal coupling between mass and heat source
- — heating and cooling system control provisions

The role of each of these "effectiveness" factors and how each relates to the "opportunity" factors is discussed in the following subsections.

3.2.2 Quantity of Mass

Most materials undergo an increase in temperature as they absorb heat from an adjacent heat source. Some materials, however, can store a given quantity of heat with much less temperature rise than others which occupy the same volume. This characteristic is referred to as "high heat capacity per unit volume".

Masonry and concrete products used in typical Canadian construction have high heat capacities per unit volume by virtue of their high mass per unit volume (density). For this reason massive construction, such as masonry and concrete construction, has become synonymous with the ability to store significant quantities of heat with moderate temperature rise.

The mechanism for temperature control and energy saving is as follows: surplus internal heat gains raise the temperature of the inside air quickly because air has an extremely low heat capacity. As the air temperature increases, heat flows from the air to the cooler structure and furnishings wherever they are in contact with the air. Solar radiation also is absorbed directly, without heating up intervening air, by those portions of the structure on which it impinges directly or by reflection. However, if these structures have low heat capacity, their temperature will increase quickly in turn and the flow of heat from the air will be reduced. In fact, with sufficient solar radiation, a light structure will heat up faster than the air. Little heat is stored and the air quickly becomes too warm for comfort.

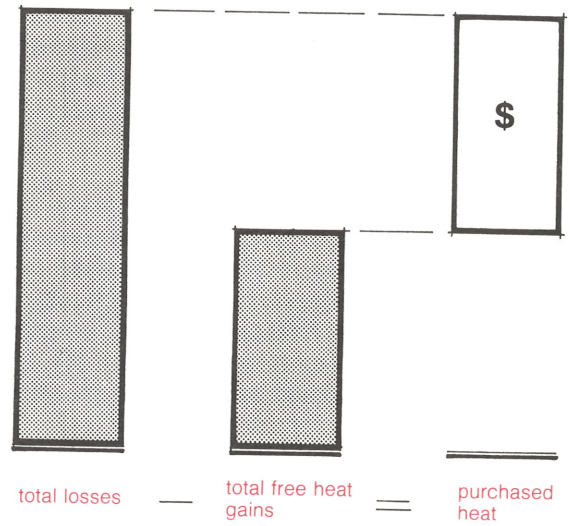


Figure 3.3A General Heat Balance

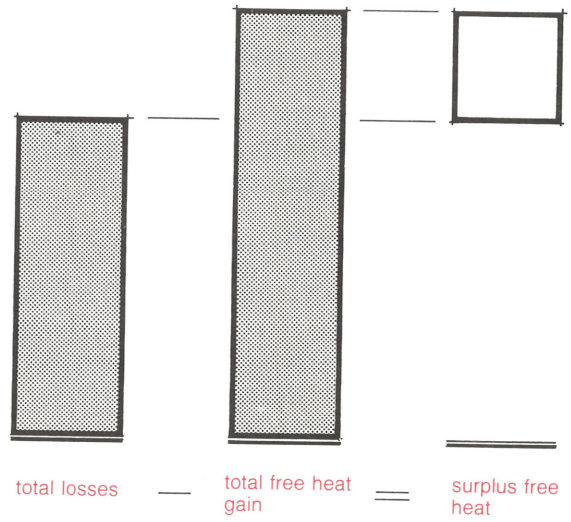


Figure 3.3B Heat Balance at Midday

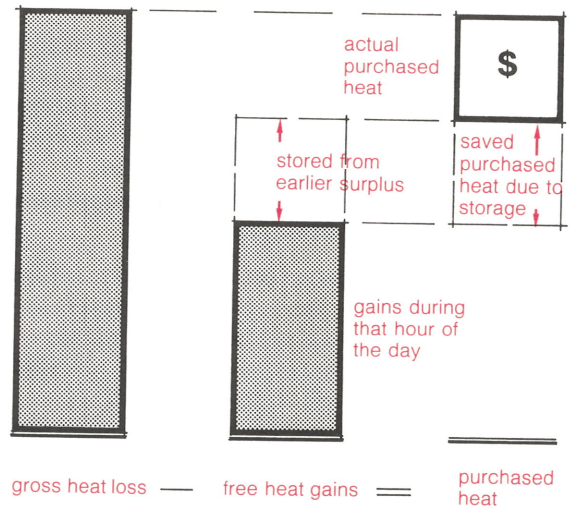


Figure 3.3C Heat Balance Later on in the Day

With a structure that has a high heat capacity the temperature of the structure does not increase very much and heat continues to flow from the air to the structure. The air temperature is thus moderated and reaches a peak temperature that is comfortable if there is enough mass. This is the comfort effect of heavy construction.

The process permits a heat energy saving in the winter and a saving in cooling energy in the summer. In the winter only **surplus** internal heat (as often occurs in the daytime in well insulated structures) causes the interior air to heat up — the rest is needed to make up for heat losses to the outdoors. If this surplus is stored in the mass, as described above, it can be used later in the day. In the summer the storage effect of mass tempers rapid temperature increases and thus forestalls or reduces the need for cooling until a later period in the day when free cooling may be available.

3.2.3 Thermal Coupling

An important factor relating to the effectiveness of mass in its heat saving role is the **thermal coupling** between heat source and mass. This is the ability of a building and its components to get surplus heat into the mass, and later, out again as needed.

Many of the heat sources in a building are not in direct contact with the mass in the structure (e.g. carpeted floors). Furthermore, the structural mass is distributed throughout the building whereas internal heat gains can be concentrated in particular areas of the building (e.g. south facing areas with windows, rooms with high equipment or appliance concentrations, etc.). All these factors tend to de-couple heat sources from the structural mass.

Poor coupling has two negative effects on the ability of mass to save energy:

(i) In the storing phase of the cycle, poor coupling prevents surplus heat from reaching the mass quickly enough and cooling or venting of warm air results, even though the mass may be still cool and has a large potential for storage. **The potential to save energy is lost immediately as the surplus heat is removed,**

(ii) In the releasing phase of the cycle, poor coupling between mass and areas of heat loss results in the inside air cooling down below acceptable minimums and the heating system turns on, even though the mass is still warm. This does not immediately waste the utility of stored heat in the structure, but imposes a lag effect — the heat takes longer to come out. If the coupling is very poor, whole portions of the building mass may stay warm until the next day's period of surplus and then the mass's potential to store heat is reduced. The mass must lose its stored heat in order to be ready to store the next day's excess.

It should be noted that, to the extent that it is variable, it is more important to have effective thermal coupling during the storing phase than during the releasing phase. This is because heat surpluses usually only last for a short period of time (e.g. when the sun is striking a particular window) and ineffective coupling results in an immediate loss of potential savings. On the other hand, release of stored energy can normally take place at a slower pace (e.g. overnight).

Three factors have a bearing on the effectiveness of thermal coupling:

- conductivity of the mass and any finishing materials covering it
- the extent to which air circulation within the building brings all available mass into play
- the location of the mass.

• Conductivity

Some designs are better than others for promoting heat transfer between available free heat and mass. For instance, quarry tile or linoleum tile will allow local surplus heat in the air and from the sun to transfer more freely to concrete floors than a thick carpet and underlay. (Figure 3.4)

Good conductivity is also desirable in the materials which constitute the mass of a structure. Since massive construction (slabs, walls) can be thick, the mass at the very centre of the structure will only be usefully coupled to surplus heat at the surface if the conductivity of the material itself is high. Otherwise the intervening material would act as insulation.

Both masonry and concrete have relatively high thermal conductivities so that a good portion of the mass in these heavy structures is available for heat storage.

Designing for adequate thermal coupling can conflict with interior finish designs, and trade-offs have to be made. For instance, thick carpeting may be a desirable feature of the interior design but this would interfere with thermal coupling. Halls and the borders of rooms and offices could be left uncarpeted as a compromise. This illustrates another advantage of massive construction: since only a portion of the structure can be properly coupled to the inside air, it is important that considerable mass be available in those areas of favourable coupling.

Return air ducting through hollow core slabs, shown in Figure 3.4, permits good local coupling with the mass in the slab and results in minimum interference with the interior layout and design.

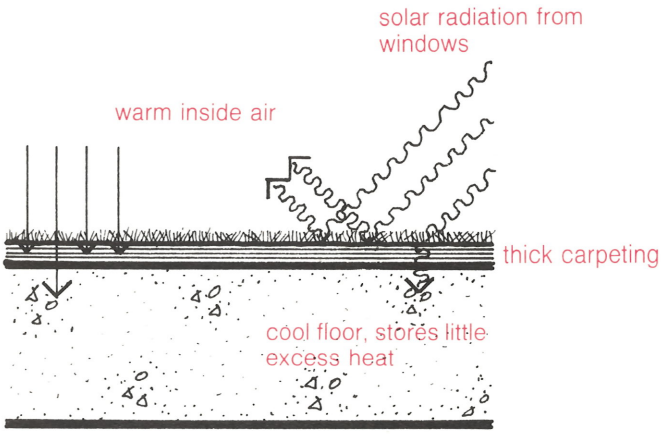
- **Air Circulation**

Thermal coupling by air circulation can be either natural or forced. Design of forced circulation systems offers some potential to improve thermal coupling. Forced air systems should be designed to induce air flow from areas of high heat gain, (areas with equipment, light fixtures, south-facing rooms, areas of activity in houses), bring this air into contact with as much structural mass as possible, and direct it to areas of high heat loss (north-facing zones or rooms, peripheral areas, etc.). Again, hollow core floor slabs or the cores of interior masonry walls can be used as integral elements of the air circulation system.

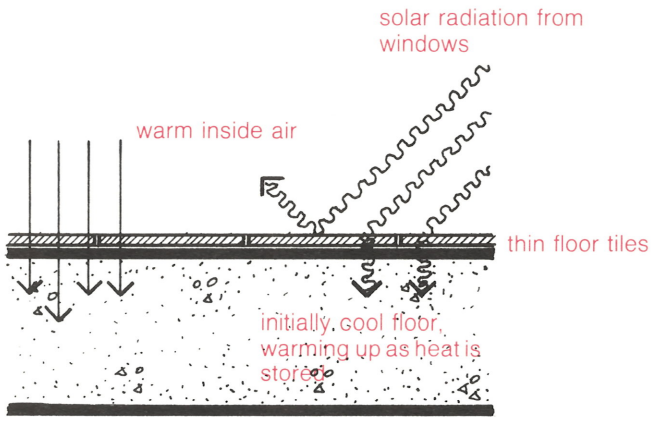
- **Location**

The effectiveness of structural mass in its thermal storage role will vary according to its location relative to heat gains and losses in a building. For example, mass that is located where sunlight through the windows will fall directly on it plays an important role in moderating temperatures and storing energy. The radiative heat is absorbed into the mass without raising the temperature of the intervening air, thus not immediately requiring modulation of air temperature. It is therefore ideally coupled to the heat source (the sun). Again interior design features can improve or hinder this process. Light coloured or sheer drapes allow sunlight to reach the mass whereas dark heavy drapes absorb the radiation and heat the air next to the window and the energy is immediately lost by conduction through the window.

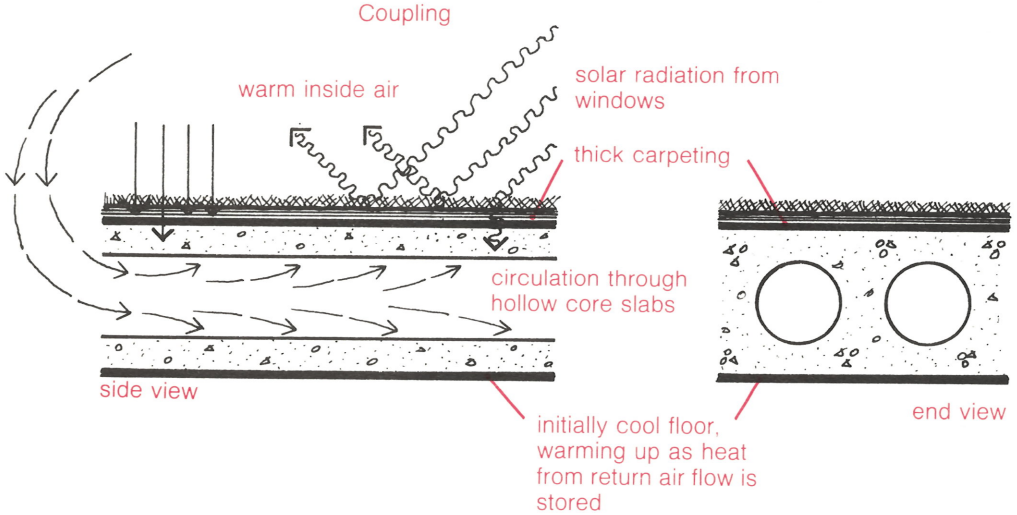
Ideally, mass should not only be located near the sources of heat gain but also near the areas of heat loss as illustrated in Figure 3.5. In the above example,



Poor Thermal Coupling



Good Thermal Coupling


warm inside air
solar radiation from windows
thick carpeting
circulation through hollow core slabs
side view
end view
initially cool floor, warming up as heat from return air flow is stored

Improved Thermal Coupling with Hollow Core Slabs by Circulating Air Through Cores

Figure 3.4 Reducing Local Resistance Separating Air and Mass

sunlit mass is not only well coupled to the heat source but also the presence of windows and exterior walls in close proximity assures that the mass will be in a high heat loss area at night. Natural convection during the release phase may be the only mechanism needed to achieve the coupling required.

If the mass is immediately on the inside of the insulation (i.e. part of the building envelope) it is very well coupled to the area of heat loss, in that all stored heat will be used before heat losses through that portion of the structure contribute to the heating requirement. This feature does not hamper its ability to store surplus heat. During the winter, mass in this location will always be ready for the next day's surplus of heat. This is an asset in buildings with regular daily periods of high internal heat gains.

Structural mass that is not located near the exterior of large buildings may be thermally coupled well enough to store high internal gains generated locally, but adequate coupling to the peripheral areas is required to allow that heat to be discharged from the mass and thus forestall the need for purchased heat. This can be achieved by forced air circulation. If gains are high and regular on a daily cycle, more coupling (i.e. forced circulation) is required. If gains are periodic, natural circulation may be enough to discharge the mass in time for the next period of high internal heat gain.

3.2.4 Temperature Control

The important role of small temperature swings of the inside air in driving the storage cycle described above cannot be overlooked. Structural mass will itself moderate large temperature swings yet it is possible to set heating and cooling thermostat settings in such a way that these systems "cut-in" before mass is given a chance to work. If the cooling thermostat is set just above average room temperatures in a cooled building, this leaves little temperature difference available to induce significant heat transfer between air and mass. Winter time surplus free heat will be removed immediately (perhaps even with the use of further energy in the cooling system) rather than stored and used as heating later. Premature opening of windows on a sunny winter day has the same effect.

Structural mass in the interior of the building will moderate temperature swings, but if the occupancy of a building requires a tighter control on temperature swings, the savings opportunity for mass will be reduced.

As a general design principle, heating system thermostats should be set at the lowest comfortable temperature and cooling system settings at the highest comfortable temperature. This will not only save energy directly, but will also allow mass to do its work both in terms of improved comfort and energy saving. The choice of high and low settings depend on subjective considerations of comfort which are in turn a function of wall and roof surface characteristics (radiant temperatures of the surfaces, quantity of direct sunlight, local drafts, etc.). Target values for low (heating) and high (cooling) thermostat settings might be 20°C and 26°C respectively during occupied hours. Variable temperature (ramp) thermostats could be used to prevent very rapid changes in interior temperature, where good thermal coupling between air and mass cannot be achieved. More discussion of temperature control strategy can be found in Reference 2.

For housing, although there might not be a cooling system that could defeat the work of mass during the heating season, the venting of hot air (i.e. opening windows) during sunny winter days should be a last resort, after full interior air circulation has been used to involve as much of the internal mass as possible (fans or furnace air circulation systems should be turned on manually or by a thermostat that is set to start when overheating occurs).

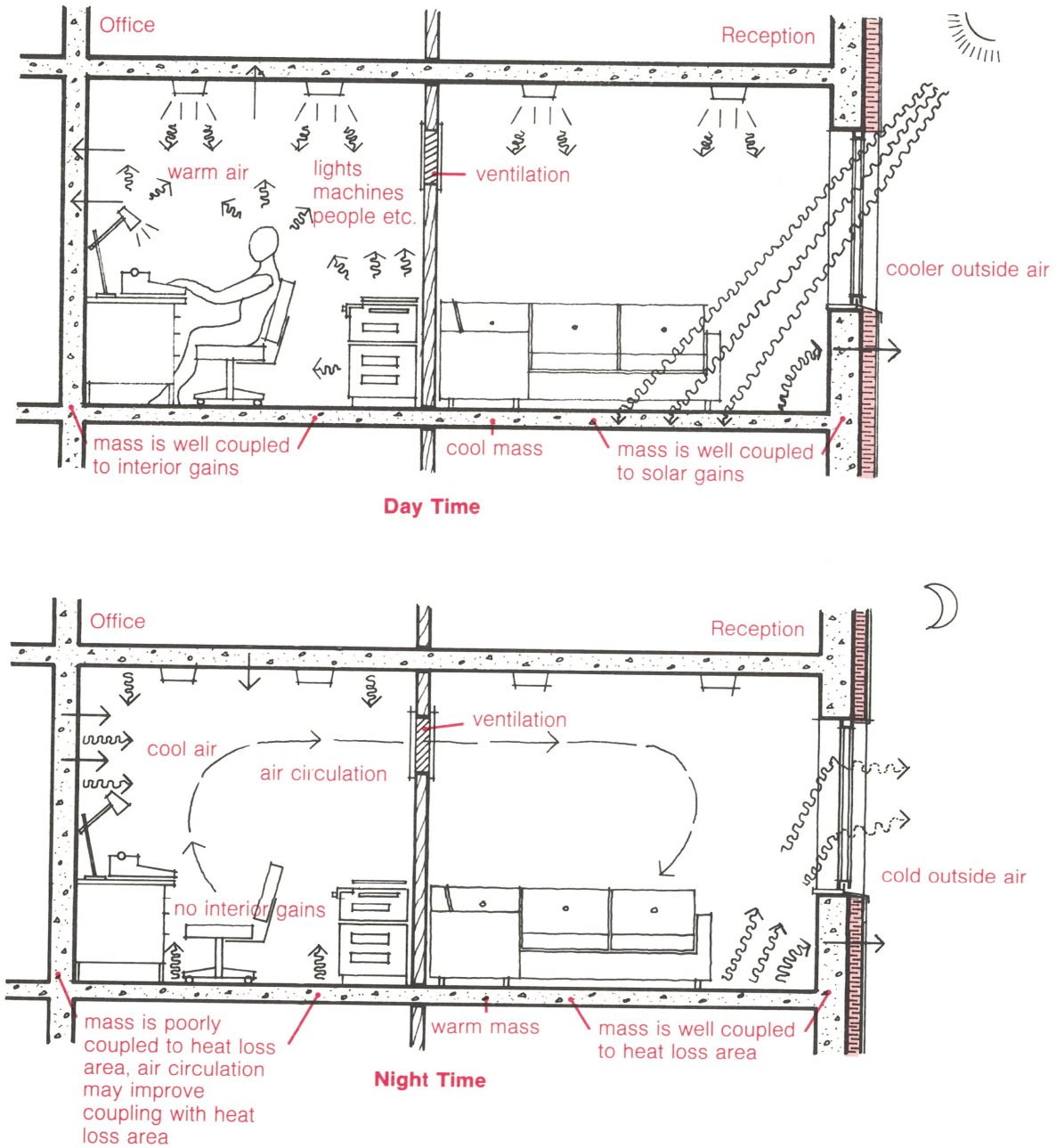


Figure 3.5 Thermal Coupling as a Function of Location.

3.2.5 Heating Plant Capacity

The inertial lag effect of mass acts to smooth the impact of low exterior temperatures on the heating system as illustrated in Figure 3.6. The important phenomenon at work here is the **lag effect** induced by the presence of mass in the pathway of heat flow through the building envelope.

Consider, for example, a thin vertical slice somewhere part way through an exterior wall. As the exterior temperature drops toward, say, an overnight low, the temperature of each such slice will tend to drop toward the level it would be at in a steady state temperature profile such as illustrated in Subsection 2.2. If, however, the subject slice has appreciable thermal storage capacity by virtue of its mass, its temperature will drop more slowly than the exterior air temperature. The next inner slice will therefore be subjected to a lower temperature difference than would otherwise obtain and the heat flow through it will be temporarily reduced. When this effect is integrated for the whole thickness of the wall, a significant temporary reduction in heat flow can result. On the other hand, the massive layers in the wall will be equally slow to respond when the exterior temperature rises in the morning, resulting in temporarily higher heat flow than in a light wall. The net result is that, other factors being equal, total heat flow (the area under the curve in Figure 3.6) is the same for light and heavy envelope components but the peak flow **rate** is significantly reduced for the massive structure.

Note that the massive layers participate in this mechanism whether they are inside or outside the insulation layer.

This effect is acknowledged by ASHRAE (6) which recommends the use of less stringent design temperatures for heating plant sizing in heavy structures.* For heavy structures with little glass area the 97.5% winter design value is recommended rather than the 99% design value, which is recommended for medium structures.** This can be translated into a reduction in heating plant size of perhaps 5% or more in Canadian cities with moderate climate.

*ASHRAE (6) uses the terms "light", "medium" and "heavy" or "massive" to differentiate between various types of construction but gives no quantitative definition of these terms.

**97.5% winter design value refers to the design temperature for which the heating system will have sufficient capacity to meet 97.5% of all weather conditions (temperatures) in January. The remaining 2.5% of the hours would be colder, so that the mass effect and other factors might be needed to maintain comfortable living conditions over those short periods.

NOTE: The benefits of mass in reducing required heating plant capacity may be reduced if night-time thermostat setback is used. The wintertime design conditions generally occur between 6 and 8 a.m. (6). As the thermostat is set forward in the morning to accommodate the comfort requirements of occupants, the system may already be running at capacity to accommodate peak loads at that time. The system is asked not only to meet peaking heat losses but also to reheat the now cool massive structure. If full advantage is taken of the mass effect in designing the heating plant, the practice of night thermostat set-back may have to be avoided during the coldest winter days.

3.2.6 Enhancing the Free Heat — Passive Solar Design

As discussed, the process of saving heat energy with mass depends on there being a surplus of internal free heat gains during winter days. Various building types and occupancies achieve a daily heat surplus naturally (e.g. large office buildings) while others can benefit from additional winter time free heat gains.

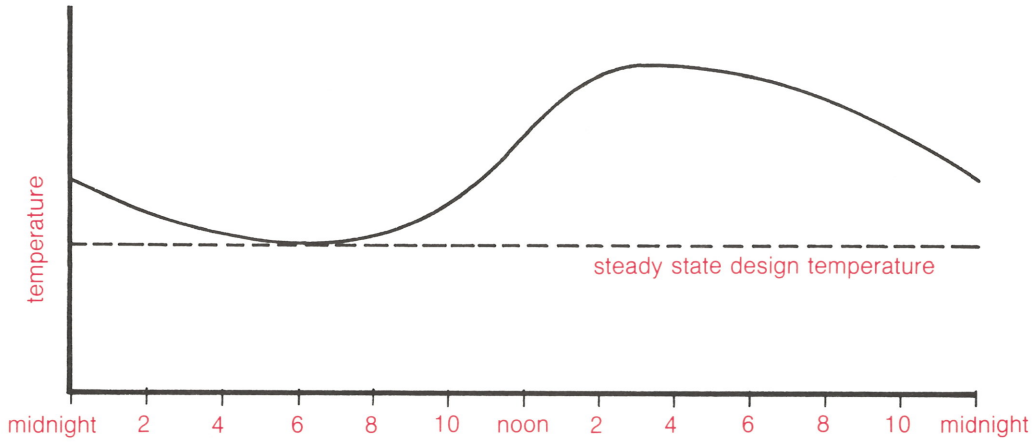
In buildings with low internal gains from people, equipment, appliances, etc. a surplus of winter time free heat will exist if the insulation levels and the proportion of south-facing window area (where the south face of the building is not shaded from the sun) are high enough. Both of these features are heat energy saving measures in themselves, but the presence of considerable mass inside the building will make better use of the incoming additional solar energy with added comfort. Furthermore, the moderation of interior temperatures by means of thermal mass allows for design of even more south window area (and therefore more free heat) for the same comfort level.

Incorporating ample south-facing windows without internal mass to store surplus heat results in overheating and may necessitate venting, thus wasting the energy that the design is intended to capture.

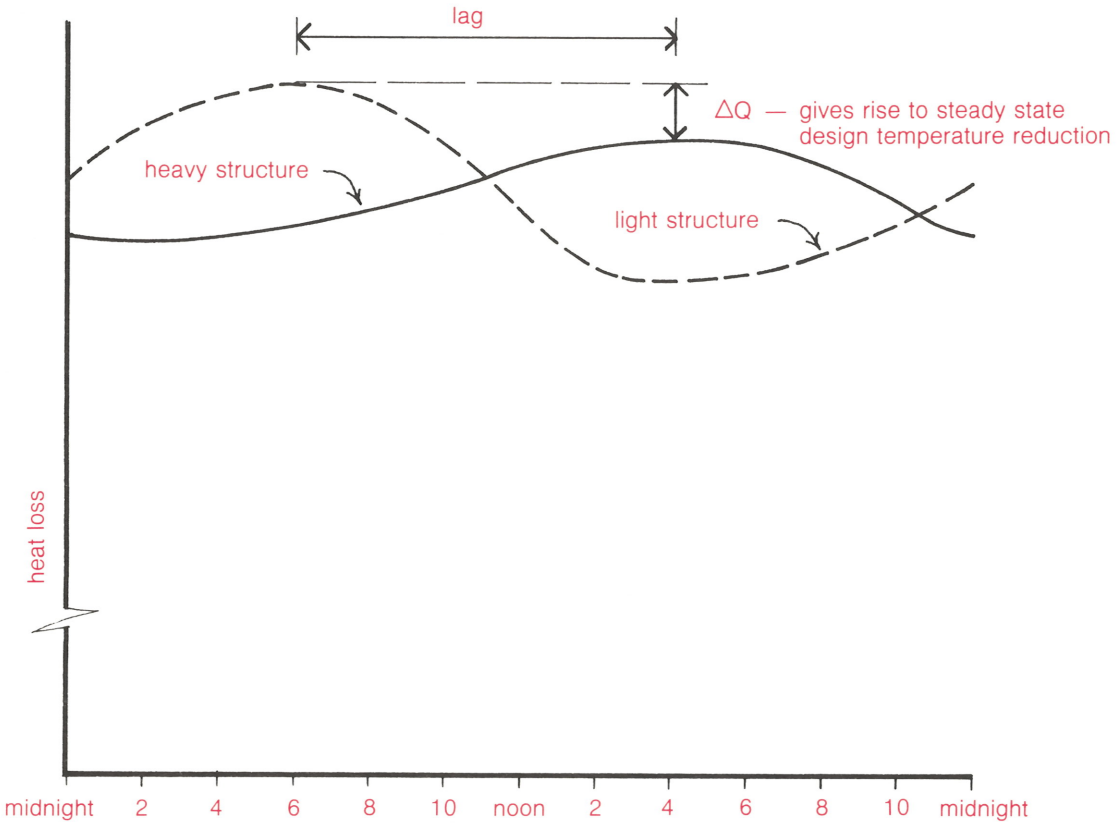
Passive solar design thus requires the balancing of the amount of insulation, south-facing window area and internal mass, while locating as much mass as possible to achieve natural thermal coupling, and providing a forced convection system to effectively couple the rest of the available mass in the structure.

The state of the art of passive solar design is developing very quickly in Canada and is presently the subject of various studies. The complex relationship among the building's heat loss characteristics and internal mass, the outdoor temperatures and the timing, amount and direction of available sunshine requires the use of computer modelling techniques to reliably estimate the passive

solar contribution to the building's energy requirements and the possibility of excessive temperature swings. As more and more such modelling is done and as more experience with this type of building accumulates, rules of thumb gradually emerge which can be used to develop preliminary designs for subsequent computer analysis. Unfortunately this experience has thus far only occurred in the area of small residential buildings. The resulting rules of thumb in this area are discussed in Section 3.4.



A Typical Winter Day Exterior Temperature Profile


lag
ΔQ — gives rise to steady state design temperature reduction
heavy structure
light structure
heat loss
midnight 2 4 6 8 10 noon 2 4 6 8 10 midnight

Corresponding Heat Loss Profiles

Figure 3.6 The Lag Effect in Heavy Structures

3.3 Reduction of Cooling Load and Cooling Energy

During the cooling season, internal heat gains from equipment, people and window solar gains, as well as solar gains through the opaque structure, all contribute to the cooling requirements of a building. Mass in the interior of a building can store some of this heat with only a moderate temperature rise, thus delaying the need for cooling. Also, solar gain absorbed in the opaque portion of the exterior structure will only affect interior temperatures hours later (lag effect) again delaying the need for cooling. Both the internal storing and the lag induced by mass in the outer walls and roof tend to reduce peak daytime cooling loads.

Heavy construction thus affords a lower cooling plant capacity, all other factors being equal.

The heat stored in the massive structure during the periods of high heat gain in the summer also represent a potential for saving in cooling energy if this energy can be vented or cooled with less energy during the cooler evenings and nights. The cool summer nights experienced by Canadian cities are thus an indicator of the potential for saving cooling energy with mass.

Thermal coupling between mass and heat source, quantity of mass, cooling thermostat control, and night time thermal coupling of mass with exterior air are all factors that affect the ability of mass to save cooling energy and cooling load.

These factors are identical to the requirements for saving heating with mass in the winter time. The difference is one of accounting, not mechanics — the energy stored in the mass represents a deferred cooling load in the summer and a potential displacement of heating load in the winter. In fact, some buildings have an overlap in cooling and heating season (cooling during the day, heating at night). Here, the mass saves daytime cooling **and** night time heating with the **same** stored energy. Thus, considerations of thermal coupling discussed in Section 3.3.2 apply equally to cooling saving effectiveness.

The cooling thermostat control can play an important role in saving cooling energy with mass. The interior mass stores excess heat gains with moderate increases in its temperature. Clearly, the higher the inside air temperature is allowed to climb during the day, the more heat will flow to the cooler structural mass and the greater is the potential for saving. Timed cooling system thermostats (called "ramp" thermostats) are available which allow the temperature at which cooling is initiated to be gradually increased from a low setting in the morning to a high setting at the end of the day according to a preset schedule determined at the design stage. The gradual temperature increase, which is not generally noticed by the building occupants, allows the air temperature to remain slightly higher than the even more gradually increasing temperature of the building mass and thus the storage mechanism continues to function throughout the day. Because mass is allowed to store energy during the high heat gain periods, the energy stored represents both a reduction in the peak load used in designing the cooling system and, assuming it can be removed by free cooling in the evening, a reduction in cooling energy required. Such a scheme is ideal for daytime occupancies where warmer evening interior temperatures are of little concern with respect to comfort of occupants. For further discussion of cooling thermostat control, see Reference 2.

Finally, there is an indirect saving in cooling energy achieved by reduction of the cooling and ventilation system capacity afforded by heavy construction. The cooling plant and fans represent in themselves major cooling loads due to the energy required in operation. Thus for each unit of peak cooling load saved there is an associated ongoing saving in cooling energy due to the reduction in load caused by the plant operation.

Quantification of these savings while properly accounting for heat gains, heat loss, mass quantity and related thermal coupling for heat storage and heat release, weather patterns, and mechanical system characteristics and control requires the detailed energy modelling of a specific building. However, once a building is in place, measures to improve the opportunities for saving with mass can be undertaken, and benefits can be monitored from year to year.

As a general design principle, enhanced thermal coupling between heat source and mass is recommended (see Section 3.2.2). Attention also has to be devoted to the thermal coupling between the mass and the cool night-time outside air. The temperature difference between inside and outside may be too small to release the stored energy by conductive heat loss through the building envelope — especially in insulated structures. A greater amount of forced ventilation during the cool night can "flush" excess heat stored in the mass at less expense than mechancial cooling.

3.4 Application of Mass Effect Principles In Various Types of Buildings

The general principles of energy saving with heavy construction discussed in the previous sections are more or less universal, yet each element plays a role

of varying importance, depending on the building type, occupancy and location. Example applications are discussed below.

- **High-Rise Residential Buildings:** Figure 3.7
For all intents and purposes, high-rise residential buildings can be viewed as a collection of individual units. Code restrictions prohibit air circulation between areas of the building so the mass on one side of the building is thermally uncoupled from mass at the other side. This places some importance on the use of mass in south-facing units. Here, the heat losses are relatively low by virtue of the fact that, except for corner units, only one wall per unit is exposed to the outside. Solar gains can be high through south-facing windows, and appliance and people gains are concentrated in relatively small areas. Thus, south-facing units in apartment buildings are potential passive solar units, with one disadvantage: they have little available space for heat storage other than the structure itself (detached houses can presumably dedicate portions or all of basement area and structure to heat storage). Heavy construction may be the only practical means of increasing the available mass to moderate living space temperatures and make best use of passive solar gains in apartments.

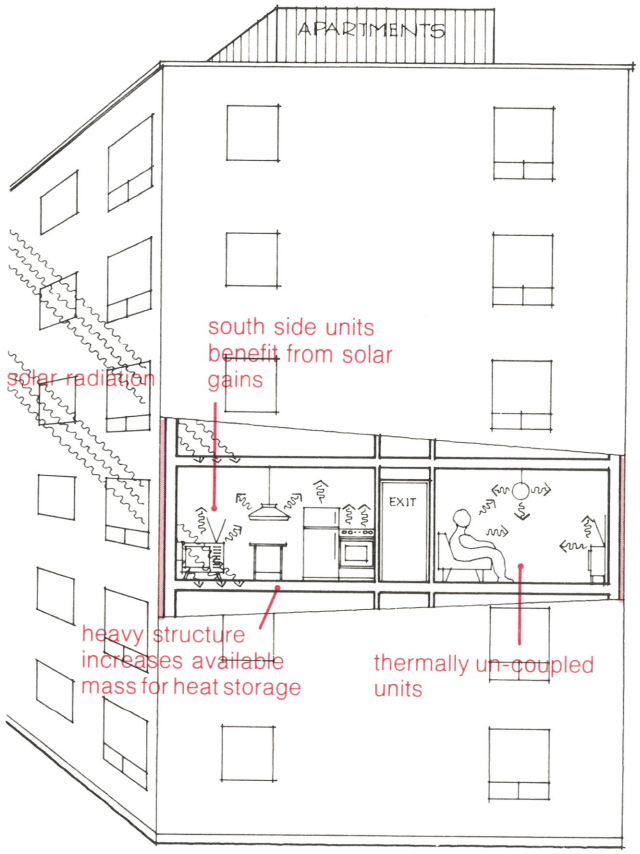


Figure 3.7 The Role of Internal Mass in Highrise Residential Buildings.

- **Highly-Insulated Houses:** (Single-family, Semi-detached, Row and Townhouses) Figure 3.8

As new housing is built to better insulation standards, the annual heat loss of the houses diminishes but window-solar gains and internal heat gains remain the same. A new breed of houses is developing in which internal heat gains and window-solar gains can be relatively high compared to heat loss. These are a particular version of passive-solar design in which insulation levels are so high that even moderate south window exposure creates the potential for excessive temperature swings. Mass placed on the interior of the insulation can play an important role in maintaining comfortable living conditions in these houses while saving heat energy in the process. A house of heavy construction can accomodate about 50% more south glazing than a house of light construction without overheating and, as a result, its purchased energy for space heating would be reduced by 10% to 20% (13). This mass can take a number of forms: masonry walls, hollow core slab floors and roofs, basement walls and slabs with externally placed insulation and party walls in multiple housing. There are also ways of deliberately increasing interior mass: fireplaces, Trombe walls, etc. (see Figure 3.9).

Bearing in mind what was said in Section 3.2.6 regarding the need for computer analysis for final design, the following guideline can be used in developing preliminary designs of passive solar

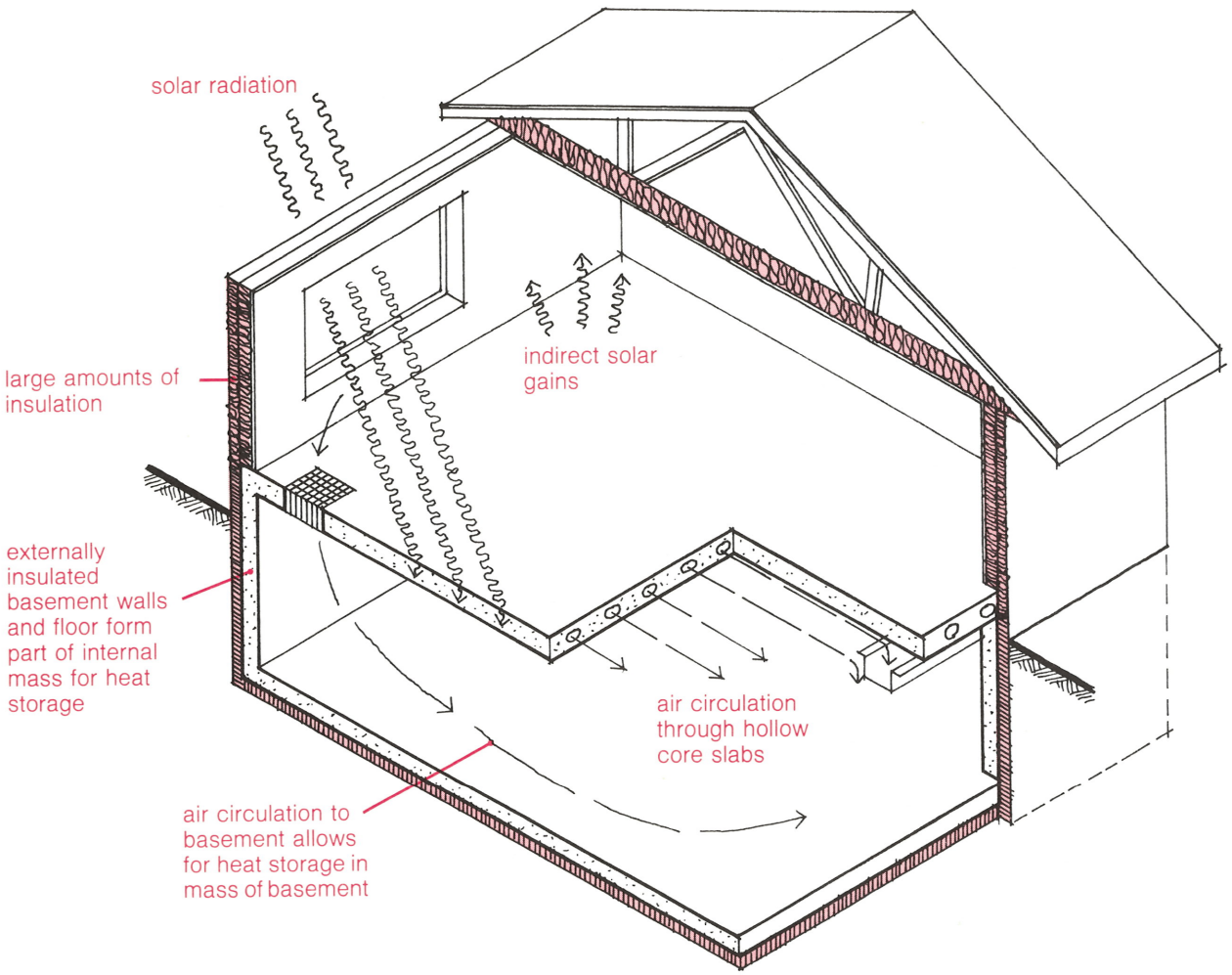

solar radiation
large amounts of insulation
indirect solar gains
externally insulated basement walls and floor form part of internal mass for heat storage
air circulation through hollow core slabs
air circulation to basement allows for heat storage in mass of basement

Figure 3.8 The Role of Internal Mass in Heavily Insulated Houses.

houses:

— Each square metre of south window can provide approximately 1.25 GJ of **useful** heat annually in houses in which the south glass area to floor area ratio does not exceed that given in Table 3.1. If more south glass is used, overheating may occur and some of the incoming solar energy may be lost through venting. Table 3.1 is a crude synthesis of data from References 13, 14, 15 and 16. It is applicable in all the main populated areas of Canada.

Table 3.1

Building Heat Loss Coefficient, G, as defined in Subsection 5.1 (W/°C)	Theoretical Maximum South Window to Floor Area Ratio (such that no overheating will occur*)	
	Light** Construction	Heavy*** Construction
100 ("super" insulated — R 10 attic R 7 walls)	0.06	0.08
200 (well insulated — R 6 attic R 3 walls)	0.10	0.14
300 (moderately well insulated — R 3 attic R 2 walls)	0.12	0.17

*additional south window area may require additional mass for a balanced design
**e.g. Normal wood frame construction with gypsum wallboard interior finish
***e.g. — wood frame walls with hollow core concrete slab floors
— masonry interior walls
— interior masonry fire place

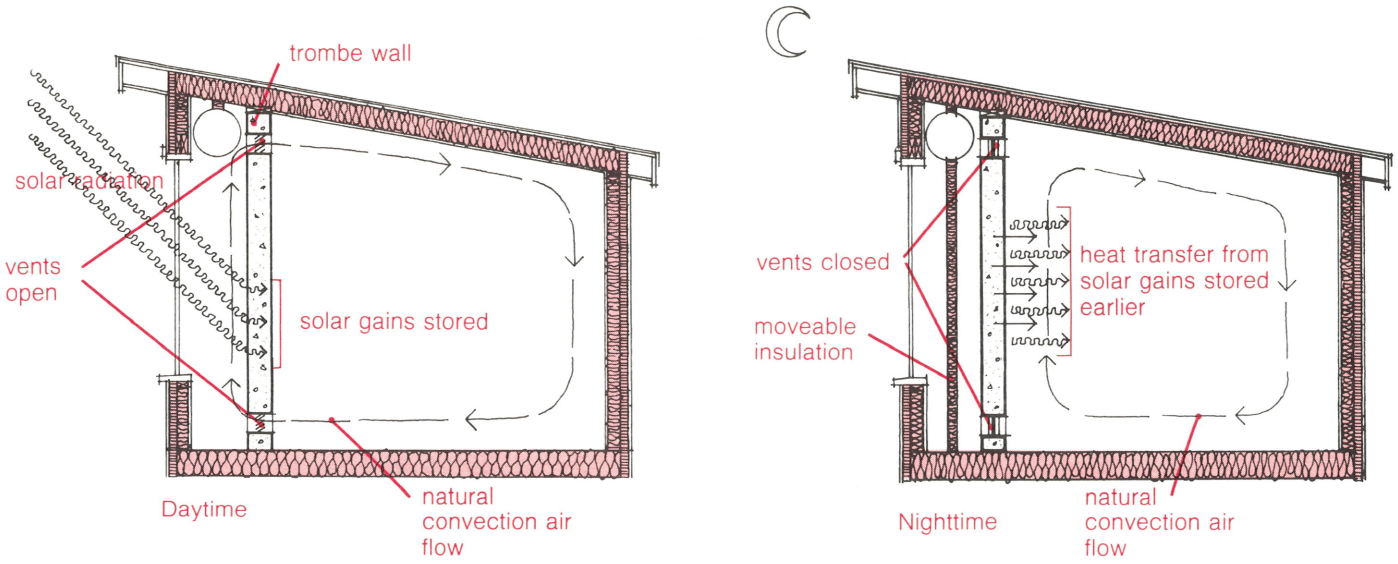


Figure 3.9 The Trombe Wall Concept

- **Large Office Buildings:** Figure 3.10

Large office buildings have traditionally had high internal gains relative to heat loss by virtue of large useable floor areas relative to exposed surface area. An entire floor of activity generates heat while only the peripheral walls and windows are losing heat. Furthermore, extensive south-facing fenestration generally adds to the surplus of interior heat. All gains are cyclic in nature and peak in the daytime.

Such buildings are ideal for heat storage via massive construction and this can save both heating and cooling energy. The physical size of the spaces involved make it important to plan the thermal coupling of interior and exterior spaces to make best use of winter heat gains and total building mass.

Hollow core floor slabs are also well suited to large office buildings, as the cores can become an integral part of the ventilation system which provides an excellent surface area to expose more of the structural mass to internal gains.

It is likely that innovation will reduce internal heat gains in office buildings (e.g. improved lighting design) but higher insulation standards will maintain the high heat gain to loss ratio that is the indicator of opportunity for saving with mass.

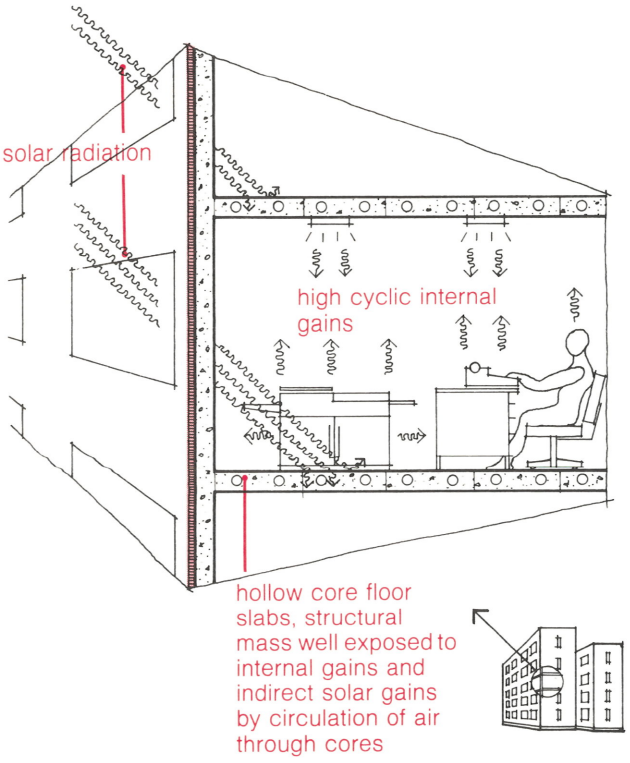

solar radiation
high cyclic internal gains
hollow core floor slabs, structural mass well exposed to internal gains and indirect solar gains by circulation of air through cores

Figure 3.10 The Role of Internal Mass in Large Office Buildings.

- **Retail Buildings:** Figure 3.11

Opportunities for saving with mass in retail buildings will vary significantly from structure to structure

depending on application, location, etc. Small retail stores often have large windows for display purposes. Solar gains through these can be excessive for the space involved and massive construction is an ideal avenue for temperature control and energy saving. Peaks in customer activity may also be a source of surplus heat requiring control.

- **Schools and Universities:** Figure 3.12
These structures are similar to office buildings in terms of internal heat gain to loss ratio but experience more cyclic concentrations of heat gains and therefore, potentially greater peaks of excess heat in local areas: filled classrooms with south-facing windows, student gatherings for sport, assemblies, etc. Thermal coupling between rooms and other areas of these buildings via forced air circulation is very important to distribute excess heat, and store this in all available mass.

Further, schools and universities have traditionally had large window areas for classrooms. Should insulation requirements of codes increase in the future, south-facing classrooms would experience high excess heat — these "passive solar" rooms would be prime candidates for the use of massive construction.

- **Warehouses:** Warehouses can differ from other types of buildings in four ways that affect their energy requirements. First the owners are often willing to allow a greater range of interior temperature. Whereas in an office building the permissible temperature range might be between 20°C and 26°C during occupied hours, in a warehouse it might be between 13°C and 29°C. Second, because of this, warehouses tend to have less insulation. In fact, since a lower interior temperature is intended, the economic amount of insulation will be lower and this may be recognized in building codes. The third characteristic of warehouses is that they usually do not house activities which generate significant amounts of internal heat gain. Finally, the mass of the inventory within the warehouse can be significant depending on the nature of the stored goods. The combined effect of these factors on energy requirements and the role of structural mass is complex and depends upon which of these factors are present and to what degree.

The possible combinations of design situations that arise from these different characteristics are numerous. Some examples are discussed in Table 3.2.

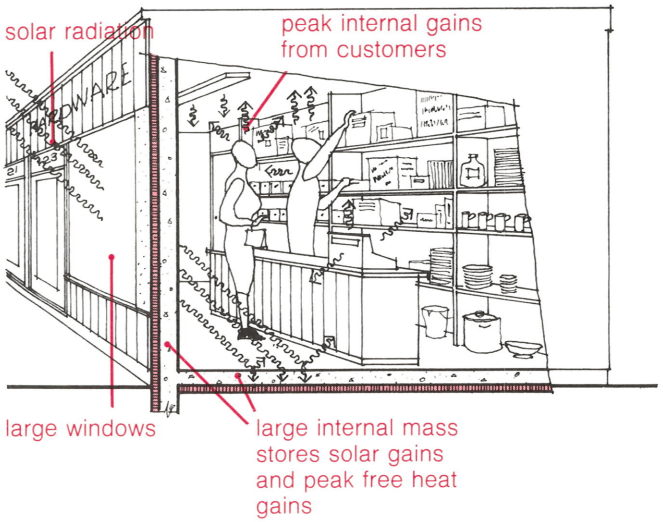

solar radiation
peak internal gains from customers
large windows
large internal mass stores solar gains and peak free heat gains

Figure 3.11 The Role of Internal Mass in Retail Buildings.

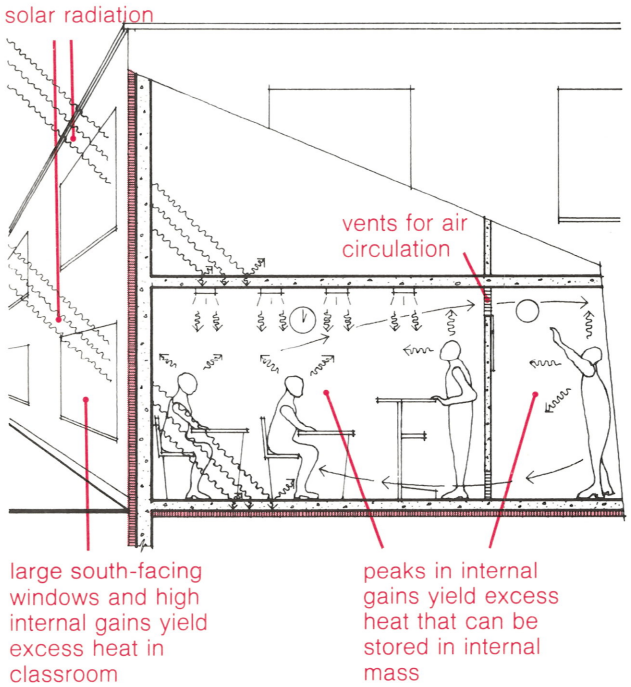

solar radiation
vents for air circulation
large south-facing windows and high internal gains yield excess heat in classroom
peaks in internal gains yield excess heat that can be stored in internal mass

Figure 3.12 The Role of Internal Mass in Schools and Universities.

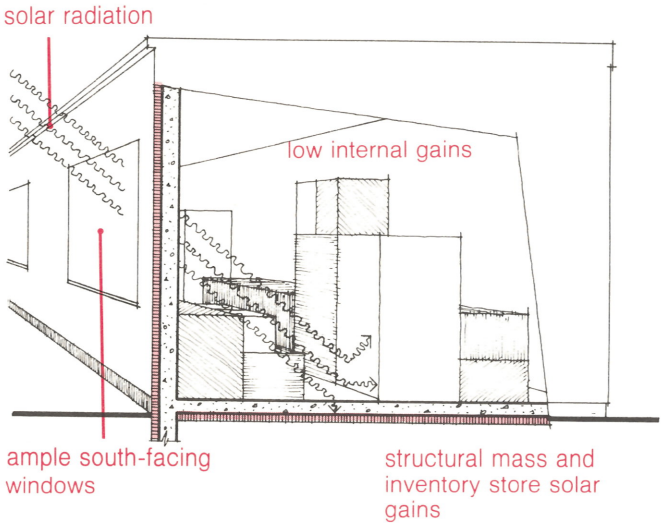


Figure 3.13 The Passive Solar Warehouse.

Table 3.2 Role of Structural Mass in Energy Consumption of Warehouses

Design Situation	Role of Structural Mass
1. Low inside temperatures are tolerable and therefore there is little insulation of the structure. Inventory is light* and only moderate temperature swings are acceptable.	Little or no insulation in the structure results in relatively high solar gains through the opaque walls and roofs. Masonry and concrete walls and roofs moderate the temperature swings due to solar gains through those components and may require less heating energy than light structures.
2. Same as 1. but large temperature swings are acceptable and inventory has considerable mass.*	Large allowable temperature swings indoors, and high mass of the inventory signals an already high heat storage capacity of the inventory. Masonry or concrete structures would allow a large array of south-facing windows to increase free heat component.
3. "Liveable" inside temperatures (20°C); moderate temperature swings allowable. Inventory has little mass.	Such structures normally require insulation to reduce heat loss. Here, the combination of insulation on the outside of the mass layer in the structure and ample south-facing windows can combine to produce and store significant quantities of solar heat — i.e. a passive solar warehouse.
4. Same as 3. but considerable mass in the inventory. See Figure 3.13.	Such warehouses could probably tolerate very large south window exposures due to combination of inventory mass and structural mass inside the insulation. The potential exists for a very low space heating requirement.

*Light and heavy inventory from the thermal standpoint is approximately the same as for the weight standpoint: heavy to lift indicates potentially lots of heat storage capacity.

3.5 References

1. Effect of Building Mass on Annual Heating Energy Requirements
   — G.P. Mitalas
   Proceedings, Second International CIB Symposium on Energy Conservation in the Built Environment
   Session 2, Copenhagen
   1979

2. Effect of Temperature Control Strategy and Building Mass on Annual Heating and Cooling Requirements of Large Office Buildings
   — G.P. Mitalas
   International Conference on Thermal Storage in Buildings
   Toronto
   November 1980

3. Relation Between Thermal Resistance and Heat Storage in Building Enclosures
   — G.P. Mitalas
   Building Research Note No. 126,
   Division of Building Research, National Research Council of Canada
   January 1979

4. The Effect of Mass on Heating and Cooling Loads and on Insulation Requirements of Buildings in Different Climates
   — S.E. Goodwin and M.J. Catani
   ASHRAE Transactions 1979
   Volume 85, Part 1

5. Residential Passive Solar Heating
   Review and Development of Design Aids
   — Okins, Leipciger, Cuplinskas, Kaminker and Associates Ltd.
   A report for the Ontario Ministry of Energy

6. Handbook and Product Directory 1977
   Fundamentals
   — American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc.

7. Solar Experiments with Passive Retrofit
   — Scott F. Keller, Arthur V. Sedvick and William C. Johnson
   Kalwall Corporation, Manchester, New Hampshire;
   published by The American Institute of Architects, Research Committee

8. The Benedictine Monastery
   — published by The American Institute of Architects, Research Committee

9. A Semi-Empirical Method for Estimating the Performance of Direct Gain Passive Solar Heated Buildings
   — Wray, Balcomb and McFarland
   Los Alamos Scientific Laboratory
   Proceedings of The Fifth National Passive Solar Conference
   Amhurst, Massachusetts
   October 1980

10. The Passive Solar Energy Book
    — expanded professional edition by Edward Mazria;
    published by Rodale Press
    Emmaus, Pa.
    Copyright 1979

11. Passive Solar Heated Warehouses
    — Bruce M. Keller, William C. Johnson, Arthur V. Sedvick
    Kalwall Corporation
    Manchester, New Hampshire;
    published by The American Institute of Architects, Research Committee

12. Rules of Thumb for Passive Solar Heating
    — J.D. Balcomb
    American Section of the Interational Solar Energy Society, Annual Meeting
    Phoenix, Arizona
    June 1980

13. Hollow Core Slabs as Storage Medium for Passive Solar Energy
    — unpublished report prepared for the Canadian Prestressed Concrete Institute by, Scanada Consultants Limited
    May 1980

14. Preliminary Performance Results for a Group of Low Energy Passive Solar Houses
    — R.W. Besant, G.J. Schoenau
    University of Saskatchewan
    August 1981

15. Measurement of the Solar Fraction of a "Base Case" Passive Solar House
    — W.C. Milne, Scanada Consultants Limited
    — S. Bennie, Institute of Man and Resources
    August 1979

16. The Thermal Mass Pattern Book
    — Total Environmental Action, Inc.
    New Hampshire, U.S.A.
    1980

17. The Effect of Building Mass on Energy Consumption for Space Conditioning in Cold Climates
    — A study for Canada Mortgage and Housing Corporation by Scanada Consultants Limited
    1982

SECTION 4
INSULATED BUILDING ASSEMBLIES

This Section summarizes the practical factors which must be considered in choosing and achieving various levels of thermal resistance in insulated masonry and concrete building assemblies. Insulating and sealing materials and methods of installation are discussed in general terms and as applied specifically to floors, walls and roofs. A number of details are given for various forms of floor, wall and roof construction. Not all of the forms of construction dealt with are recommended. Some forms, which provide only marginal performance but, because of their low first-cost, are commonly used, are included in order that their shortcomings can be pointed out and in order to encourage the use of the best details when these forms of construction are used.

4.1 Materials

When considering materials for insulation, vapour barrier and sealants in noncombustible construction, the restrictions of building codes in this regard must be borne in mind. (See National Building Code, 1980, Sentence 3.1.4.5(2).)

4.1.1 Insulation

The following is a discussion of the characteristics of the insulation materials commonly used in masonry and concrete buildings:

Mineral Fibre Batts and Blankets

— Consist of fibres of glass or steel mill slag spun together with a binding agent into a blanket-like roll or strip of various lengths and thicknesses. Available in widths to fit standard framing spacings in wood or steel framing (steel stud batts). Formerly available paper-backed batts with integral vapour barrier have recently been taken off the market due to concerns about the flame-spread rating of the backing and because a separate polyethylene vapour barrier is now recognized as a more effective approach. Thus the only batts now available are the "friction fit" type, which are slightly wider than the stud space they are intended to fit so that they are held in place by edge friction.

— Used as frame wall or ceiling insulation.

— Although not classified as "noncombustible" due to the presence of the binder, this material would contribute very little fuel in a fire and has a low flame-spread rating.

— Very high porosity and permeability. This material relies almost entirely on the surrounding materials to restrict the movement of air and water vapour. If installed so as to completely fill a cavity, mineral fibre provides sufficient resistance to air movement to prevent convection currents within the cavity; however if it is surrounded by air spaces, convection currents can greatly decrease the effective thermal resistance (Figure 4.1).

— Although the thermal resistance is reduced if the material is damp, it is largely inert to water and will regain its original thermal resistance if dried.

— Makes virtually no contribution to the structure. It is very compressible and tearable and must be installed in cavities which have their own inherent structural integrity and which will protect the insulation from such forces as wind and flowing water.

— Although the thermal resistance per unit thickness is toward the low end of the scale, this material still provides one of the lowest costs per unit of thermal resistance.

— Mineral fibre batts should always be specified by both R value and thickness since batts of different R value can be the same thickness and since compressing a batt to fit a cavity reduces its thickness as indicated in Figure 4.2. The standard batts are —

R 1.2/64 mm
R 1.4/70 mm R 1.4/73 mm
R 1.7/89 mm
R 2.1/89 mm R 2.1/111 mm
R 2.4/89 mm R 2.4/127 mm
R 2.8/146 mm
R 3.5/152 mm R 3.5/184 mm
R 4.9/216 mm R 4.9/229 mm R 4.9/254 mm
R 5.4/286 mm
R 5.6/292 mm
R 6.1/305 mm
R 6.3/330 mm
R 7.0/388 mm

Rigid Glass Fibre Board

— Similar to batts but increased binder content and higher density result in much greater compressive strength.

— May be faced with asphalt-impregnated kraft paper, in which case its permeability is decreased.

— Used as cavity wall insulation or roof insulation.

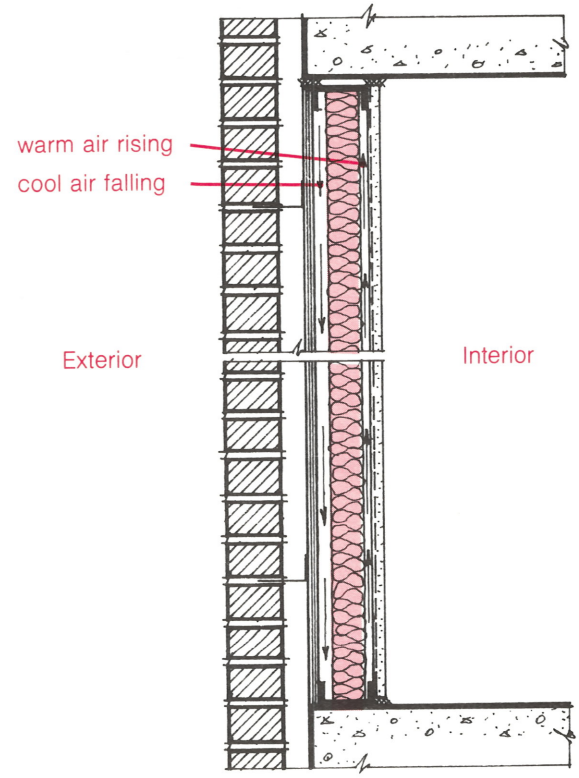


Figure 4.1 Loose Fitting Insulation Resulting in Convection Currents

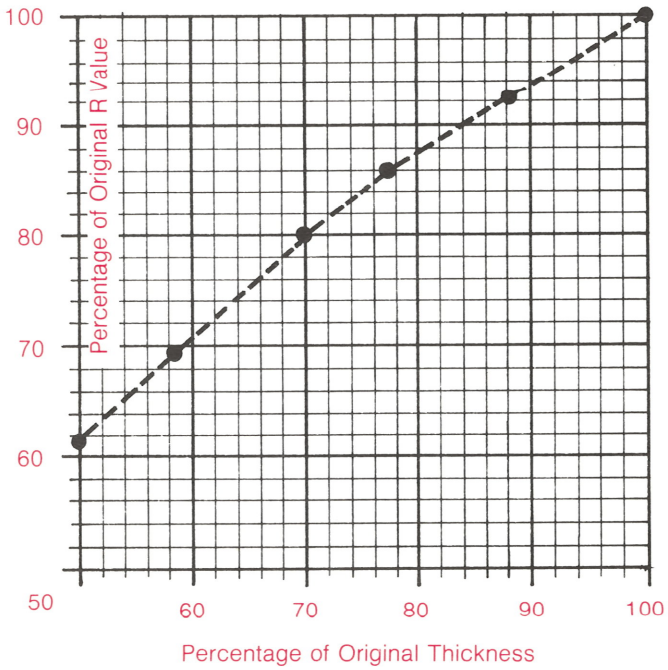


Figure 4.2 The Effect of Compressing Batt-Type Insulation on its Thermal Resistance

— Medium cost per unit of thermal resistance.

— Lowest thermal expansion and contraction of all rigid board insulation (1×10^{-5} m/m•°C)

— Available in thicknesses from 19 mm to 100 mm in increments of 6 mm.

Expanded Mica (Vermiculite) Loose Fill

— Consists of granules (about 6 mm Ø) of expanded mica.

— Poured into ceilings, cavities of cavity walls and cores of hollow core block walls.

— The type used in masonry walls is treated with asphalt to repel moisture, but even this type will absorb moisture if subjected to prolonged exposure.

— High cost per unit of thermal resistance.

— Noncombustible.

Expanded Polystyrene Beadboard

— Manufactured by a heat process which expands polystyrene beads and fuses them into blocks which are subsequently cut into sheets.

— The Canadian General Standards Board (CGSB) standard calls for three types.

Type	Density	R Value/mm
1	16 kg/m³	0.0257
2	20 kg/m³	0.0277
3	24 kg/m³	0.0298

— This material has the lowest strength and rigidity of any of the rigid board insulations and it is easily damaged on a construction site.

— The fusion process leaves voids between the beads which make the material fairly permeable to water vapour but also makes it susceptible to water damage in applications where it might be very wet and subject to freeze-thaw cycling such as in inverted membrane roofs or where the insulation is in contact with soil. Types 2 and 3 are more resistant to such damage.

— Lowest cost per unit of thermal resistance of the rigid board types often offsets disadvantages listed above.

— Fair amount of thermal expansion/contraction (about 7×10^{-5} m/m•°C).

— Available in thicknesses from 13 mm to 508 mm in increments of 12.7 mm.

Extruded Polystyrene Board

— Manufactured by extruding a liquid polystyrene foam resulting in a closed cell structure with no voids between the cells.

— Very high strength and rigidity and very resistant to water damage.

— Very low permeability.

— One of the highest R values per mm but also high cost per R.

— Thermal expansion/contraction same as beadboard (about 7×10^{-5} m/m.°C).

— Available in thicknesses of 25, 38, 50, 63, 75 and 100 mm.

Urethane and Isocyanurate Board

— Closed cell plastic foam with refrigerant gas in cells to give highest thermal resistance. Facings of paper or aluminum foil help to retain the gas in the cells and thus avoid or delay reduction in thermal resistance with age. Aluminum foil facings are more effective.

— Good strength but not as high as extruded polystyrene.

— Low permeability.

— High thermal expansion/contraction (10 to 20×10^{-5} m/m.°C).

— Urethane board is available in thicknesses of 19, 25, 38, 50, 63 and 75 mm.

— Isocyanurate board is available in thicknesses of 12 to 57 mm in increments of 6 mm.

Phenolic Foam Board

— Open cell phenol-formaldehyde foam with paper facings.

— Strength not quite as high as urethane board.

— Open cell structure results in high permeability and relatively low thermal resistance per unit thickness.

— Lowest flamability of the foam plastic insulations.

— Lowest thermal expansion/contraction of the foam plastic insulations (3 to 7×10^{-5} m/m.°C).

— High cost per unit of thermal resistance.

— Available in thicknesses of 29, 41 and 52 mm.

Foamed-in-Place Urethane

— Essentially the same material as in urethane board but manufactured on-site by spraying or pouring a self-adhering mixture of chemicals and foaming agent onto the surface to be insulated.

— Ideal for insulating irregular shapes.

— Difficult to control quality and thickness of final product under on-site conditions.

— When applied to irregular shapes it is difficult to apply a covering material to provide fire protection (see below). Chemically treated cellulose fibre can be sprayed on top of the urethane using a water medium. This reduces the surface flame spread characteristics. However it is still classed as a combustible material and thus will not likely be accepted as an exposed surface finish in buildings where noncombustible construction is required. Also it is unlikely to comply with the requirements for protective coverings for foam plastics. (See below)

Foam Plastics in General

All of the foam plastic insulations (polystyrene, urethane, isocyanurate, phenolic) are flammable and have high surface flame spread characteristics. They must therefore not be exposed on the interior of buildings. The National Building Code requires that they be covered by an acceptable interior finish material (i.e. with a flame spread rating of less than 150) in buildings where combustible construction is permitted, and, in buildings where noncombustible construction is required, by one of various protective coverings, depending on the flame spread rating of the insulation and other factors. (See National Building Code, 1980, Sentence 3.1.4.5(2).) These materials are also subject to gradual deterioration when exposed to the ultra-violet rays in sunlight. They should, therefore, be covered on the exterior as well.

4.1.2 Vapour Barriers

As was pointed out in Section 2, very often a separate vapour barrier is not required. This is the case where the components of the building assembly (usually the interior finish) can be sealed to prevent air leakage and the interior finish, either on its own or with the assistance of paint coatings, provides the small amount of resistance to vapour diffusion needed. Where this is not the case and a separate vapour barrier is required, the best choice will usually be polyethylene film for the following reasons:

- It is available in very large sheets and thus can be installed with a minimum of joints.
- It has very high vapour resistance.
- Its cost is quite low.
- If thick enough (0.15 mm), it is reasonably strong and resistant to damage during construction.

4.1.3 Sealants and Fillers

Although the term "sealant" usually means a material used to seal a joint between two other materials and the term "caulking" usually means a material used to fill cracks and openings, the difference between these two definitions is subtle enough that the two terms are often used interchangeably. Since many materials can be used for both purposes, this Guide will not linger on the distinction.

An ideal sealant will tolerate less-than-perfect surface conditions in terms of moisture and dirt on the surfaces it must adhere to, (however, cleanliness during installation should never be neglected) will accommodate large variations, due to building movements and thermal movements, in the dimensions of the joint it is placed in and will retain its adherence and elasticity over a long period of time.

There are so many sealants now available, each approximating this ideal to a greater or lesser extent usually in proportion to cost, that it is difficult to give any general guidance in this area. As a class those sealants sold as "acoustical" sealants have been found to give good performance but they are not suitable for exposed applications because they do not form a skin.

Regarding the installation of sealants, the dimension of a bead of sealant should be greater in the direction in which it is expected to be deformed than in the transverse direction (Figure 4.3). This will result in less strain of the sealant with joint movement. In order to accomplish this it is sometimes necessary to partially fill the joint with some other material before the sealant is applied. "Ropes" of extruded polystyrene foam or other closed cell compressible foams such as EPDM rubber are often used for this purpose.

These materials can also be used as joint fillers or gaskets. A wide variety of densities and qualities is available. Some materials such as PVC foam become hard and brittle at low temperature and should only be used on the interior side of the insulation.

4.1.4 Fire Stopping

The National Building Code defines a fire stop as a draft-tight barrier within or between construction assemblies that acts to retard the passage of smoke and flame. Building codes require that fire stops be provided to cut off completely all concealed horizontal and vertical openings occurring between stories and between top stories and roof spaces.

Where noncombustible construction is required, fire stopping material must be of essentially noncombustible material. Asbestos-cement board, gypsum board or other noncombustible materials having a melting point above 760°C, such as sheet steel, are acceptable. Flashings of galvanized steel or copper can thus serve as fire stops within walls if properly located. When a compressible fire stop material is required, particularly when such material is being used in a location where appreciable thermal resistance is necessary to reduce thermal bridging, the use of low binder mineral fibre insulation is recommended. Normal mineral fibre insulation, because of its higher binder content, does not meet the National Building Code definition of noncombustible material and is thus unsuitable for this purpose.

Where combustible construction is permitted, the National Building Code allows the use of a wide range of materials for the purposes of fire stopping.

Several of the Figures illustrating subsequent parts of this Section indicate the provision of fire stopping in some of the locations typically required by building codes. Users of this Guide should, however, refer to the applicable building code governing the proposed construction to ensure that fire stopping is provided in all of the locations where it is required.

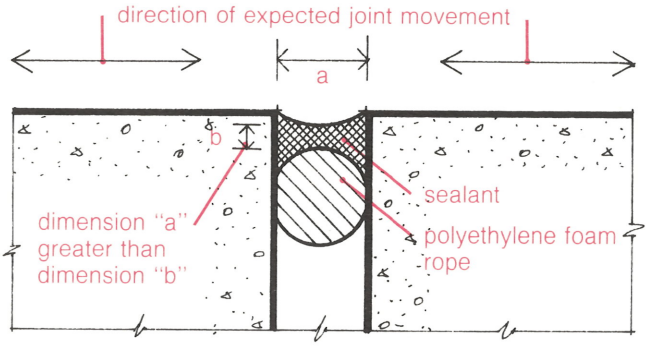


Figure 4.3 Correct Proportioning of Sealant Bead

4.2 Installation of Insulation

In contrast to frame construction, which inherently provides cavities suitable for the installation of low cost batt insulation, insulating masonry and concrete construction usually involves the application of insulation to large flat surfaces. There are basically two approaches to doing this:

- Supplementary framing (e.g. steel studs) can be added to provide cavities for the installation of batts and to support subsequent components of the assembly.

- Rigid insulation can be fastened to the surface by various means.

The use of supplementary framing with batts is most common in the insulation of walls and will be discussed in Subsection 4.4.

Rigid insulation can be fastened to masonry or concrete surfaces with adhesives, with various types of furring and mechanical fasteners and by impaling it on adhered pins ("stick clips").

- **Adhesives:** This is the most obvious method of fastening anything to a large flat surface and there are a number of adhesives available for this use. However this method has the following disadvantages:

— It is difficult to be sure of attaining required degree of cleanliness of the surface under on-site conditions.

— It cannot be used for exterior applications in cold or wet weather.

Selection of the proper adhesive is important. It should be compatible with the type of insulation being used. The vehicles or thinners in some adhesives will attack foam plastic insulation. Also some protein-based adhesives can provide nutrition for fungi and other micro-organisms unless they have preservatives included in their make-up.

The adhesive should not be applied in daubs. The use of daubs of adhesive creates an air space between the surface and the insulation. If the insulation is on the inner surface of the assembly, warm moist air circulating in this space will cause condensation. If the insulation is on the outer surface of the assembly, cold air circulating in this space will "short circuit" the insulation.

It is better to apply a full bed of adhesive or a grid of beads of adhesive (Figure 4.4). A full adhesive bed is the preferable method from an adhesion point of view but where it is on the cold side of the insulation (e.g. applying insulation to the interior surface) it may act as a vapour trap preventing drying of any moisture which penetrates the interior air/vapour barrier. In this situation therefore the grid approach should be used.

The use of adhesive to apply insulation to the underside of floors or ceilings is a somewhat doubtful practice. Unless a high degree of quality control is exercised in installation, the adhesive may fail under the constant pull of gravity.

- **"Stick Clips":** In these circumstances the use of stick clips may be a better choice. These are thin metal or plastic pins with a large perforated flat head at one end. The head is fastened to the concrete surface with a high quality adhesive which keys into the perforations. The clips are applied in a grid pattern, then the insulation is impaled on the pins and secured in place with a type of spring washer which is simply pushed over the end of the pin against the

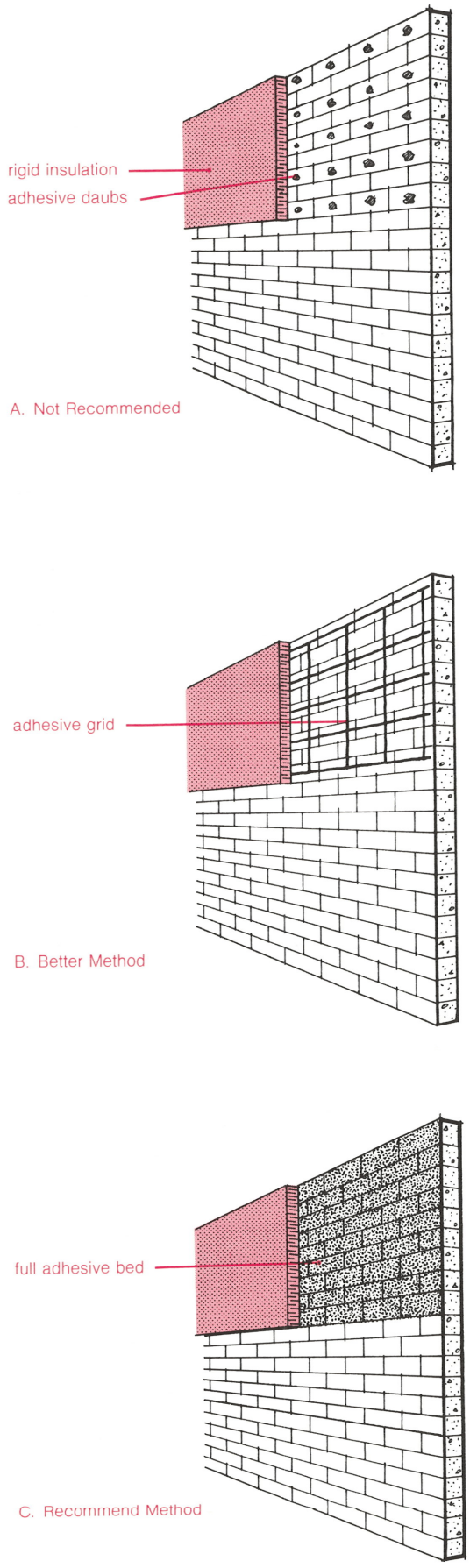


Figure 4.4 Application of Rigid Insulation with Adhesives

insulation. Sharp "teeth" on the washer grip the pin (Figure 4.5). Although this method also relies on adhesive the entire surface does not have to be covered, thus making it easier to clean the surface and permitting the use of high performance (and hence costly) adhesives.

Stick clips cannot, however, be relied upon to support a ceiling finish applied under the insulation. This should be supported by a separate suspension system held up by wires cast into or mechanically fastened to the concrete. The insulation must, of course, be penetrated or cut to fit around these wires.

Stick clips should also be used for wall installations where uneven surfaces or protrusions require bending or local compression of the insulation thus producing tension in the adhesive.

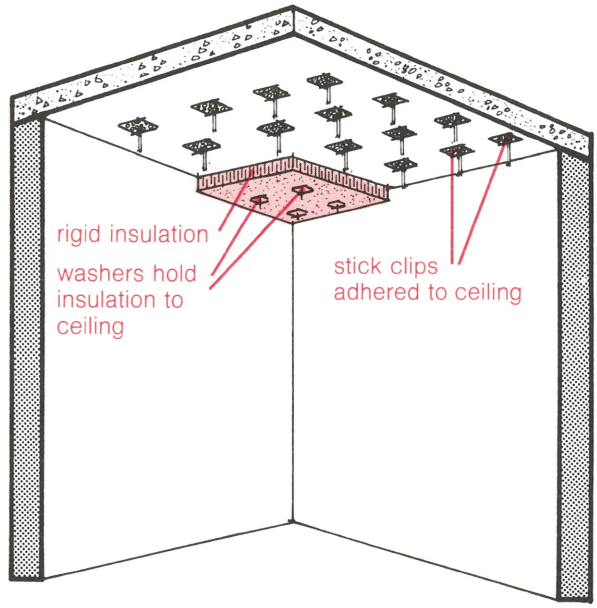
Stick clips are available in lengths to accommodate insulation up to 125 mm thick.

- **Furring Systems:** There are a number of types of wood or metal furring which can be applied over the insulation and fastened, through it, to the masonry or concrete surface. Figure 4.6 illustrates some of the approaches. The furring is usually applied along the joint between two insulation boards so that one piece of furring contributes to the support of two insulation boards. This may require special preparation of the edges of the insulation such as grooving to accept the legs of the U channel in Figure 4.6B. Depending on the size of the insulation boards and the amount of support required by any subsequent finish, furring may also be applied in the middle of the insulation boards. This may also require special preparation of the insulation.

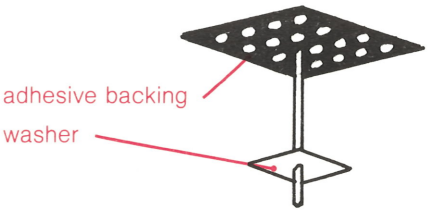
The insulation may be held in place temporarily prior to application of the furring by light daubs of adhesive. These should be very light to avoid holding the insulation away from the surface as mentioned under adhesives.

The furring can be fastened with powder-driven fasteners or a special type of concrete nail which is driven into a pre-drilled hole. The available length of fasteners usually limits the thickness of insulation to about 100 mm.

Where this method is used to apply insulation to the inside of a wall or ceiling, the interior finish is applied by screwing or nailing it to the furring members. This would also apply where this method is used to apply insulation to the outside of a single wythe wall. The insulation must be protected from the weather by a covering such as metal siding or stucco on lath. The siding or lath is fastened to the furring members.

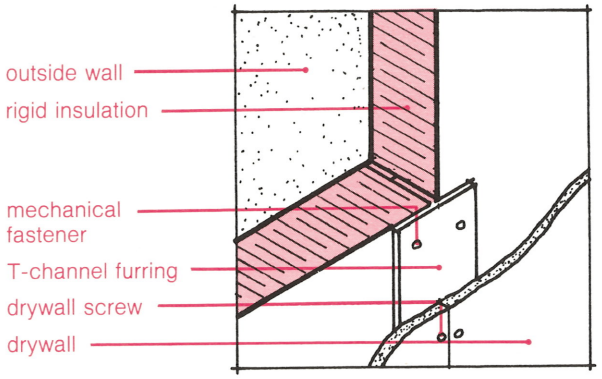


A. Rigid Insulation Installed on Ceiling by Stick Clips

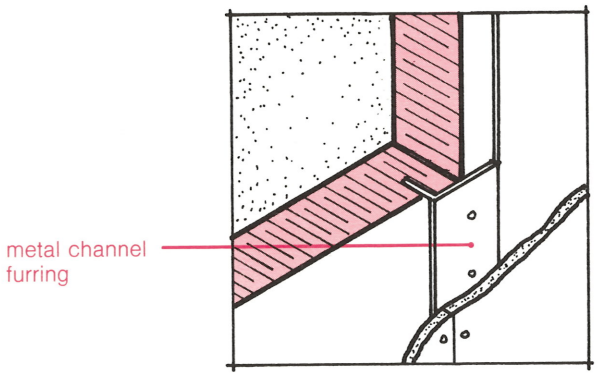


B. Stick Clip

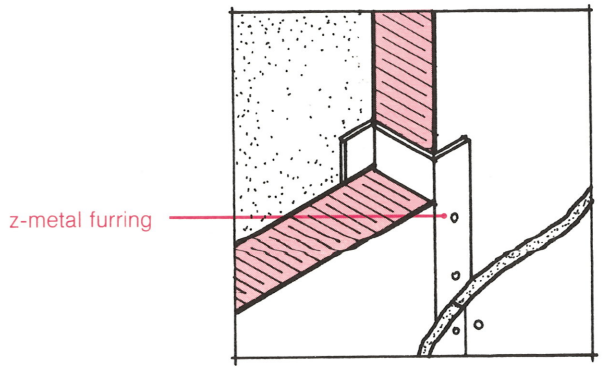
Figure 4.5 Effective Method of Installing Rigid Insulation on Ceilings



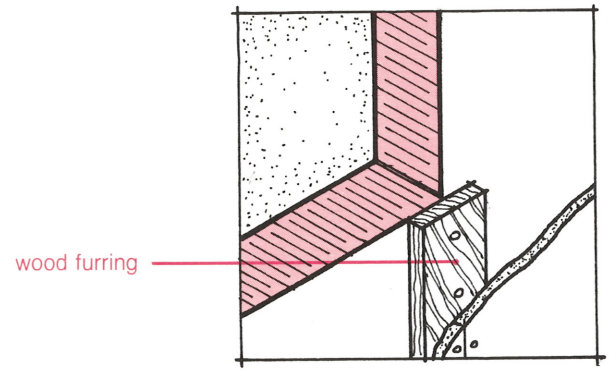
A. T-Channel Furring



B. Metal Channel Furring



C. Z-Metal Furring



D. Wood Furring

Figure 4.6 Furring Systems

4.3 Insulating Floors

The application of insulation to floors presents a number of unique problems, not the least of which is the fact that it involves overhead work, which makes it difficult for the workmen to pay continuous attention to detail and quality.

One positive aspect is that a separate air/vapour barrier is seldom required. The floor is usually close to being monolithic with a minimum of penetrations. Even if any penetrations are not perfectly sealed, exfiltration/condensation is unlikely to occur since the airflow will probably be inward unless the building is pressurized. This is not to suggest that such penetrations should not be sealed as well as possible. They still contribute to overall building leakage.

In addition to the general considerations discussed in Subsection 4.2, there are three special concepts relating to the insulation of floors which require consideration — the possibility of using batt insulation in a ceiling suspended below a floor, the possibility of insulating on the upper side of a floor and the treatment of ribbed and waffle floors.

4.3.1 Suspended Ceilings

The placement of insulation in a ceiling space suspended below a floor (Figure 4.7) has the attraction of permitting the use of mineral fibre, the lowest cost type of insulation. However, if the ceiling space is not filled with insulation, great care is required to ensure —

a) that the ceiling surface is tightly sealed around its perimeter and at any penetrations, such as light fixtures, in order to prevent the cold outside air from penetrating above the insulation, thus by-passing it, and

b) that the perimeter of the ceiling space, which is, in effect, a wall, is insulated.

If the ceiling space is entirely and tightly filled with insulation these concerns are alleviated but this is difficult to do with batts. It can be done by blowing in loose mineral fibre insulation although this cannot be inspected to ensure completeness except, perhaps, by infra-red thermography.

Another consideration here is that the mineral fibre insulation will be thicker than any of the rigid insulation for the same R value. Thus either the building will have to be somewhat higher or some headroom will be lost.

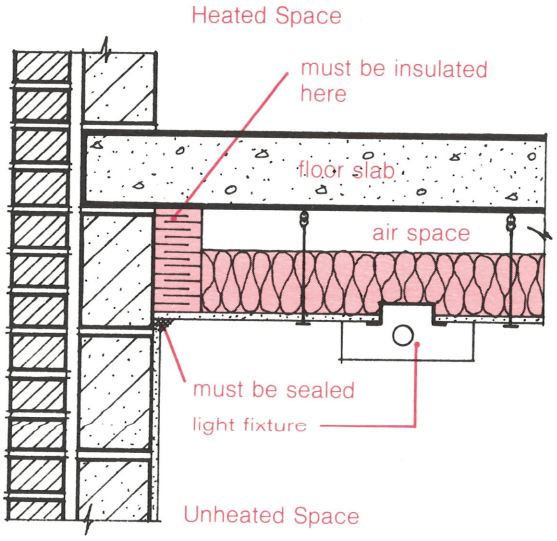


Figure 4.7 Insulated Ceiling Below Floor

4.3.2 Insulation Applied to the Upper Side of a Floor

Many concrete floors have a concrete topping coat

applied above the structural slab in order to provide a very smooth, level surface for the application of floor finishes. Where this is the case, the possibility exists of placing a rigid insulation between the topping and the slab as shown in Figure 4.8. This has the advantages that the insulation can simply be laid on a smooth flat surface and no further exterior finishing operations are required for the underside of the slab. However it also has several drawbacks including the following:

— An expensive insulation with high compressive strength must be used.

— The entire floor slab will be at or near the exterior temperature and thus subject to thermal expansion and contraction. A slip plane will have to be created between the slab and the insulation to isolate the insulation from this movement.

— Cross-walls and columns intersecting the floor, which necessarily penetrate the insulation, form major thermal bridges to a large exterior heat loss surface.

— The mass of the slab does not participate in storage of excess internal heat gains as discussed in Section 3.

In sum this method cannot be recommended.

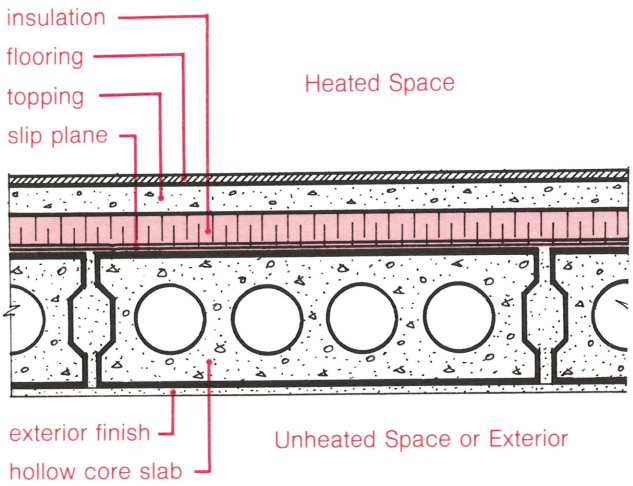


Figure 4.8 Rigid Insulation Between Concrete Slab and Topping

4.3.3 Treatment of Ribbed and Waffle Floors

Although the advantages of applying insulation on the upper side of a floor apply especially to these types of floors, the disadvantages also apply; so we will discuss here only ways of insulating the undersides of such floors.

As indicated in Subsection 4.1.1, foamed-in-place urethane combined with a topping of sprayed cellulose is ideal for insulating this type of surface where —

— it is acceptable from a fire point of view, and

— concerns about on-site quality control are taken care of by contractual arrangements and/or the reputation of the insulation contractor.

If the ribs are spaced closely enough, rigid insulation can be fastened to their bottom edges using stick clips or one of the furring systems shown in Figure 4.6. Alternatively a suspended ceiling can be installed and insulated with mineral fibre insulation. In either of these cases the concerns outlined in Subsection 4.3.1 regarding air penetration and perimeter insulation require particular attention.

With series-produced ribbed precast concrete floor slabs, it is possible for the producer to arrange for

custom-molded form fitting rigid insulation. The polystyrene beadboard molding process lends itself fairly readily to custom shapes.

Figure 4.9 illustrates the various approaches to insulating ribbed and waffle floors.

4.3.4 Placing Insulation in Forms

If insulation is placed in the floor formwork prior to casting, the natural bond of the concrete will help to support the insulation. However this should be supplemented by mechanical fastening such as wires protruding through the insulation which then become cast into the concrete.

Using this method, adequate precautions must be taken to prevent the supports of reinforcing steel from penetrating the insulation, thus displacing the reinforcing steel.

4.3.5 Summary

Taking all the above factors into account, it seems likely that, in most circumstances, the most trouble-free approach to insulating floors is to fasten rigid insulation directly to the underside using stick clips and covering the insulation with a separately suspended ceiling.

4.4 Insulating Walls

There are so many different types of masonry and concrete walls that it is difficult to make any general observations beyond those in Subsection 4.2. This Subsection therefore presents a number of different wall assemblies in the form of detailed cross-section drawings with accompanying observations and comments specific to each assembly. As mentioned at the beginning of Section 4, not all assemblies presented can be expected to give good performance under all conditions although all have given acceptable performance in some conditions.

4.4.1 Solid Masonry Walls

In resisting rain penetration, solid or cavity-less masonry walls rely on the capacity of the masonry to absorb water which penetrates the exterior surface during the rain and dissipate the absorbed water to the exterior afterwards. The likelihood of this approach being successful is dependent on a number of factors:

- The thickness of the wall. Older, very thick masonry walls had more than enough absorptive capacity for rainstorms of normal duration. This is less true of modern thinner walls.

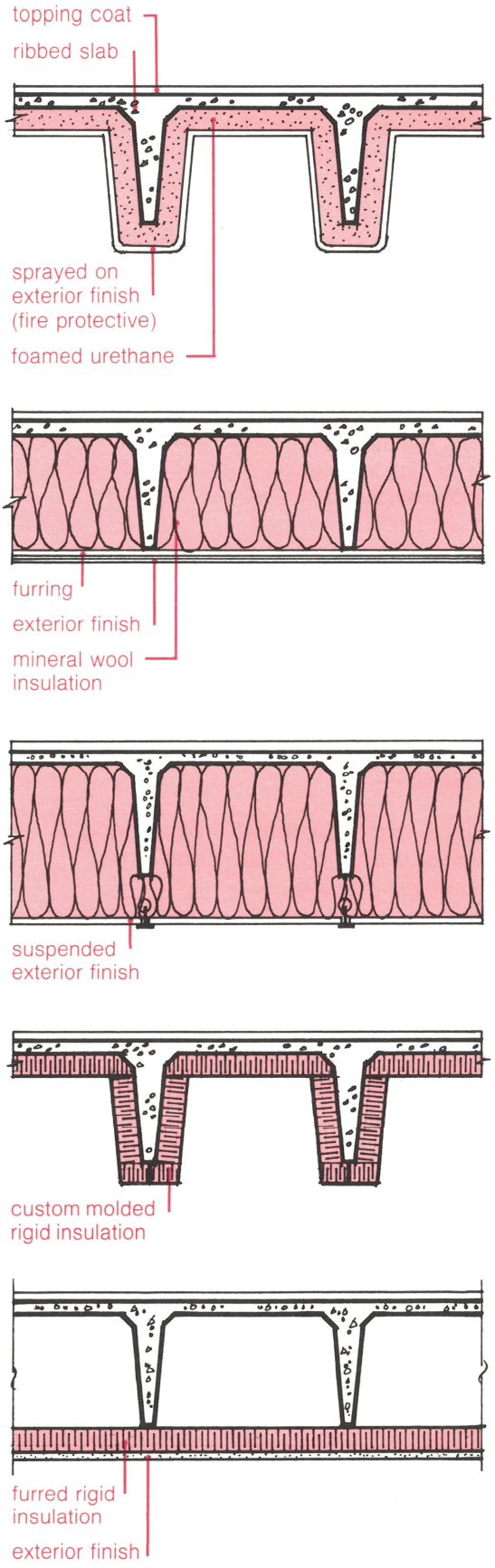


Figure 4.9 Methods of Insulating Ribbed Floors

- The presence of high winds during rainstorms. The difference between the outdoor and indoor pressures on the windward side of a building forces the water absorbed in the capillaries of the masonry materials away from the outer surface and toward the inner surface. If it is simultaneously being replaced at the outer surface by more rain or if the pressure difference is great enough, water will exude from the inner surface.

- The length of the interval between rainstorms. If a wall's absorptive capacity is still partially taken up with water from a previous storm there is greater chance of its becoming saturated during the next storm, with the result that additional wind-driven rain striking the outer surface will force water to exude from the inner surface.

- The integrity of the wall. Incomplete or poorly bonded bed and head joints and other penetrations of the wall provide paths to the interior by which the rain can short circuit a significant amount of the wall's absorptive capacity.

This suggests that solid masonry walls are most likely to be successful —

— in areas which do not have frequent long rainstorms accompanied by high winds,
— in low buildings, and,
— where care in workmanship and in ensuring compatibility between the mortar and the masonry units can be relied upon.

NOTE: CSA Standard A371 "Masonry Construction for Buildings" notes that cavity walls (see Subsection 4.4.2) should be used where superior resistance to water penetration is required.

The use of insulation in solid masonry walls introduces some other considerations. As was pointed out in Section 2, placing the insulation on the interior, the only practical location in such walls where exposed masonry is the desired exterior appearance, lowers the temperature of all of the masonry to close to the outdoor temperature. If rain is followed by below freezing temperatures, as is common in eastern Canada, the water still absorbed in the masonry will freeze and create expansive stresses, which may eventually cause serious deterioration. Also, even if the outdoor temperature is above freezing, the temperature drop across the masonry, and hence the difference in vapour pressure which drives the drying mechanism, will be rather small so that the wall will have less chance of drying out between rainstorms.

The fact that solid masonry walls must usually be insulated on the interior is another consideration with

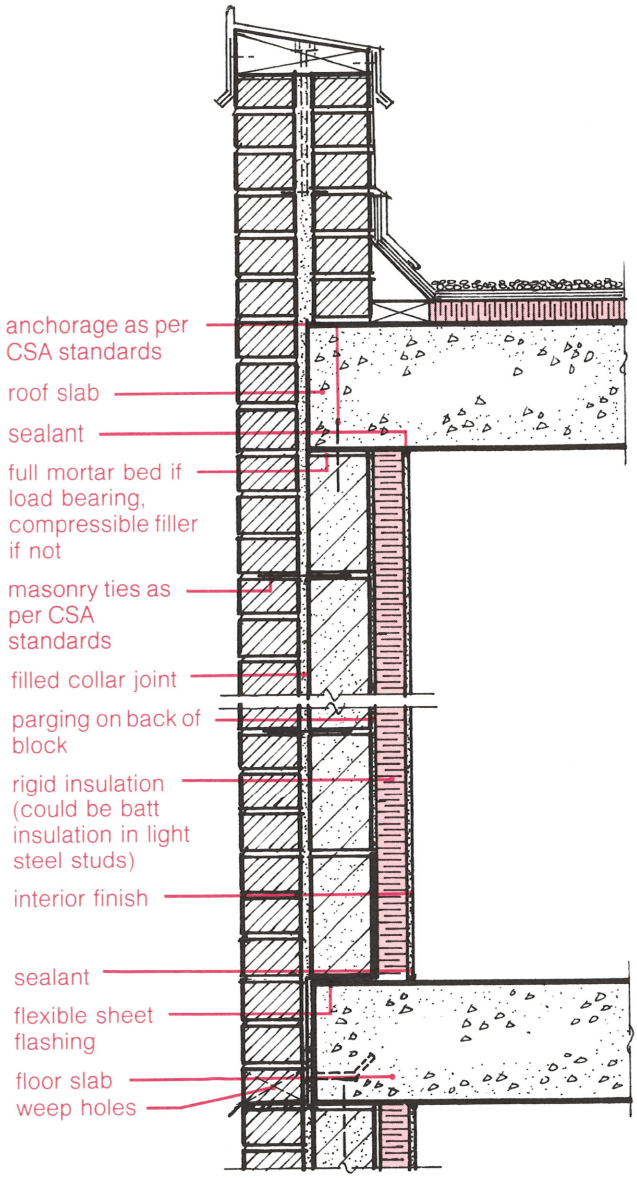


Figure 4.10 Double Wythe Solid Masonry Wall. (See text, 4.4.1, regarding suitable conditions for usage.) Note major thermal bridges at slabs.

this form of construction. As was pointed out in Subsection 2.2.4, this makes significant thermal bridges unavoidable, subjects the entire wall to thermal movement and negates the energy-related advantage of the wall's mass.

Also in some types of buildings, such as warehouses, the excellent resistance to mechanical damage of a masonry interior surface is desirable, thus making interior-applied insulation undesirable. Exterior-applied insulation with a protective covering of metal siding or stucco allows single wythe masonry to be used in these situations.

Figures 4.10 to 4.13 show different types of solid masonry walls.

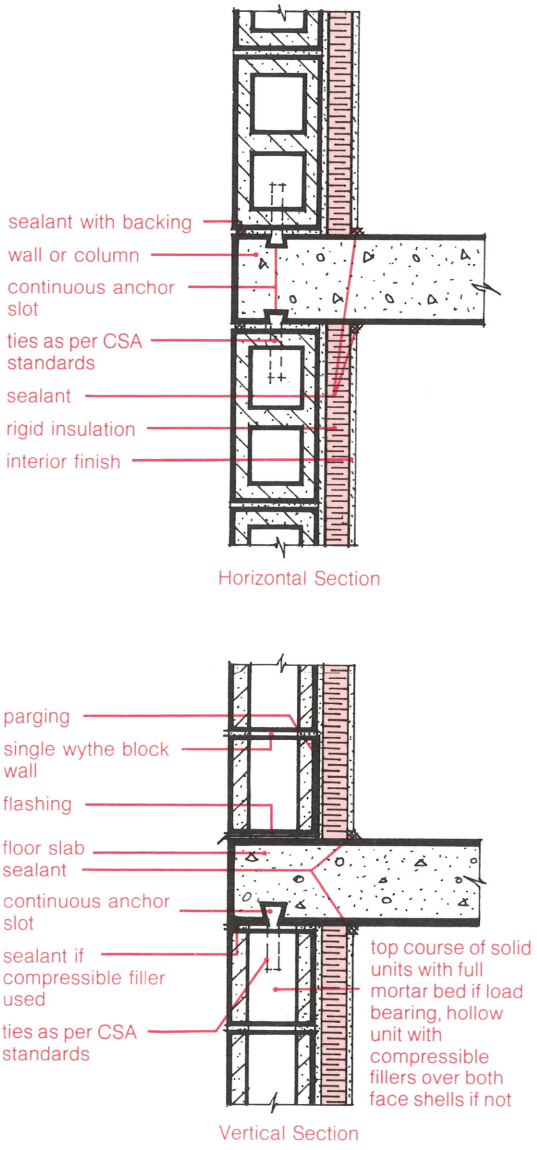

sealant with backing
wall or column
continuous anchor slot
ties as per CSA standards
sealant
rigid insulation
interior finish
Horizontal Section
parging
single wythe block wall
flashing
floor slab sealant
continuous anchor slot
sealant if compressible filler used
ties as per CSA standards
top course of solid units with full mortar bed if load bearing, hollow unit with compressible fillers over both face shells if not
Vertical Section

Figure 4.11 Single Wythe Masonry Wall. (See text, 4.4.1, regarding suitable conditions for usage.) Note major thermal bridges at slabs.

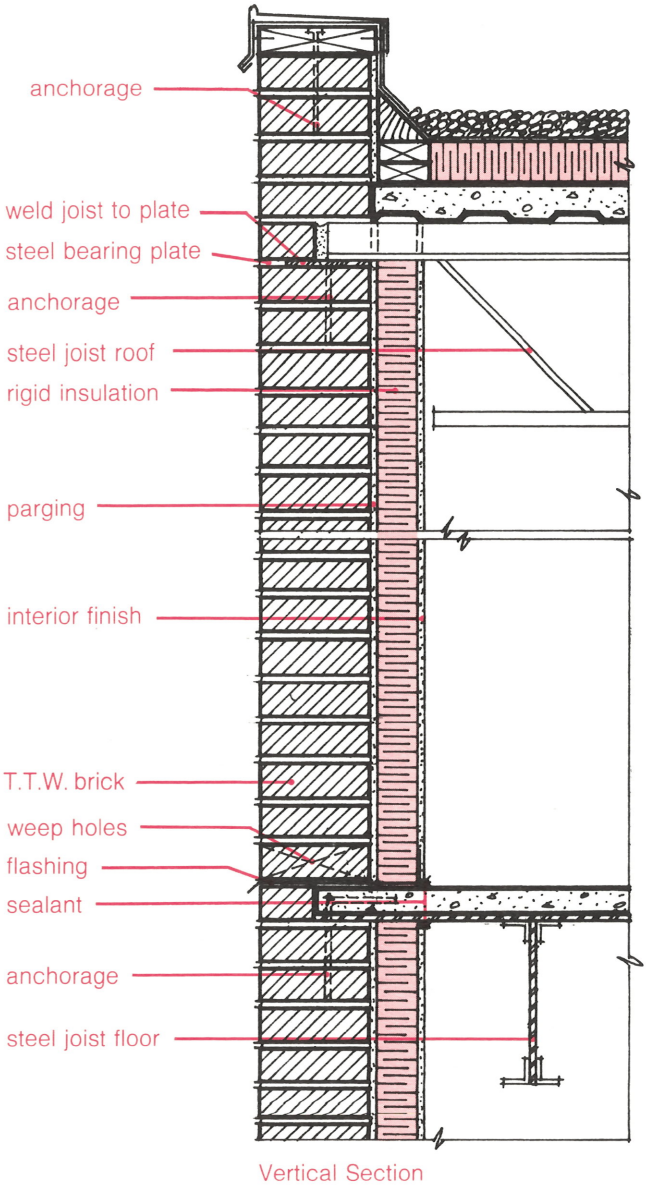


Figure 4.12 T.T.W. (Through the Wall) Brick Wall. (See text, 4.4.1, regarding suitable conditions for usage.)

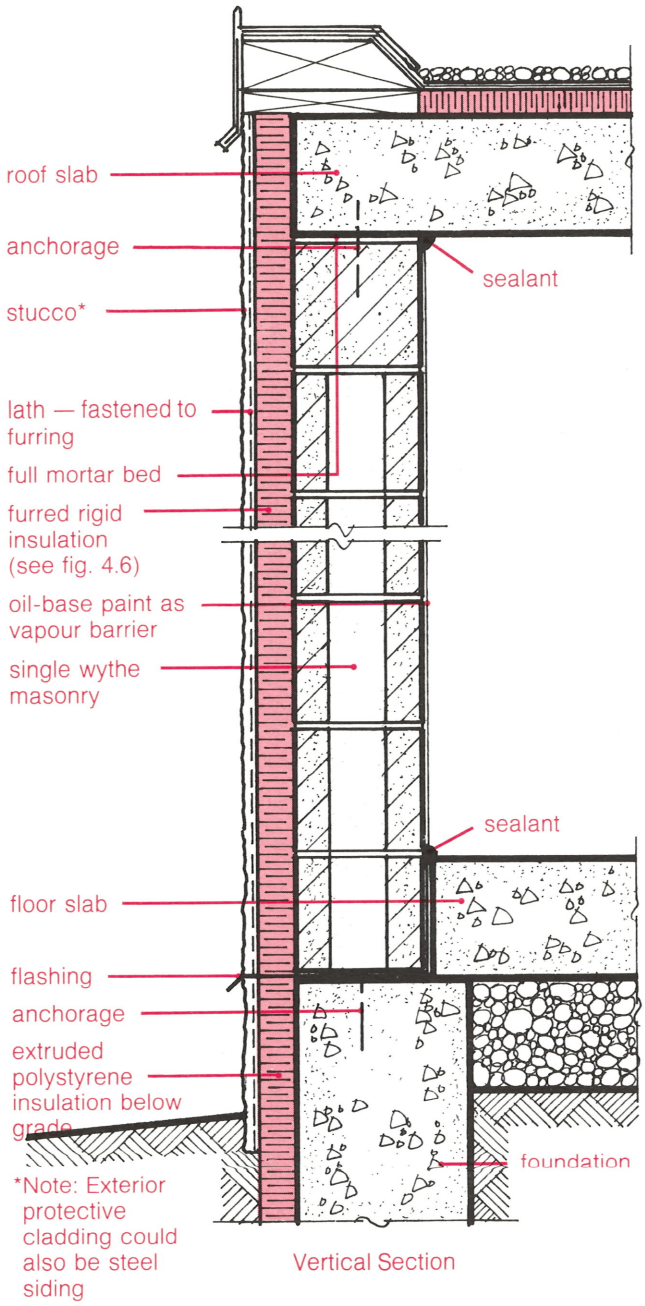


Figure 4.13 Single Wythe Masonry Wall with Exterior-Applied Insulation.

4.4.2 Masonry Cavity Walls

Cavity walls are based on a different approach to resisting rain penetration than solid walls, an approach more likely to be successful in adverse conditions. Rain is assumed to penetrate the outer wythe and to then fall down the cavity until intercepted by an internal flashing which directs it back out of the wall through weep holes. The success of this approach is dependent on the following conditions being achieved.

— a clear cavity (i.e. not filled with insulation) not obstructed or bridged by mortar fins or droppings and wide enough that the water penetrating the outer wythe will not bridge the cavity due to its own momentum (at least 25 mm, wider is preferred) (see also Subsection 4.4.4).

— an impervious and comprehensively detailed flashing positively sloped to the outside

— sufficient unobstructed weep holes to handle the flow. (The minimum specified by codes will suffice.)

Achieving these conditions requires care at both the design and the construction stages. Much more could be said about means of achieving these conditions; however, as much of such discussion is applicable regardless of the amount of insulation in the wall, it is best to omit it from this Guide and refer the reader to the many excellent references on the subject of masonry wall construction listed at the end of this Section. It is perhaps only necessary here to point out that a cavity wall approximates the rainscreen approach discussed in Subsection 2.4.2. In fact it has been suggested that, by including vent holes at the top of the cavity in addition to the weep holes at the base, the air pressure in the cavity will be allowed to equalize with the exterior pressure and the rainscreen condition will be achieved. Although there has not been enough experience with this approach to develop reliable "rules of thumb" it is suggested that such vent holes should provide a total area equal to approximately half of the total weep hole area.

The existence of a cavity presents the opportunity for placing the insulation on the outside of the inner wythe, thus avoiding the disadvantages of interior-placed insulation discussed in Subsection 2.2.4. There are, however, limitations on the amount of insulation that can be placed within the cavity. The function of the ties between the outer and inner wythes is to transfer all of or at least some portion of the wind load on the outer wythe to the inner wythe. When the outer wythe is subject to positive (i.e. inward) pressure the "ties" actually act as compression "struts". Since the ties must be thin enough to fit within the mortar beds, their unsupported length with currently available products is limited by slenderness considerations to about 150 mm. Thus, if a 25 mm clear cavity is to be maintained, 125 mm is the maximum amount of insulation that can be placed in the cavity. This will result in an overall R value of between R4 and R5 depending on the type of insulation used. If a higher R value is required the insulation or some portion of it must be placed on the interior side of the inner wythe. Thus interior insulation placement, despite its many disadvantages, (see Subsection 2.2.4), cannot be ruled out.

Figure 4.19 shows a promising but untried method of placing thick insulation in the wall cavity. The cavity is filled with insulation thus permitting the transfer of

positive wind pressures through the insulation and permitting the uses of light ties since they need act only in tension. The outer surface of the insulation is grooved for drainage. This method would require the use of insulation with high mechanical strength and low moisture absorption.

The following points should be borne in mind when considering placing insulation in the cavity:

— The wall must normally be placed in two stages — inner wythe followed by insulation plus outer wythe. While this does not present any problems in low rise construction, the practice in high buildings of placing both wythes from inside the building without scaffolds or swing stages is made more difficult.

— Care must be taken to remove mortar fins on the outer face of the inner wythe and to ensure that slab edges are aligned to provide a smooth surface to which to adhere the insulation.

— Care must also be taken in fitting the insulation around the ties, flashing and shelf angles.

— A high strength flashing material, such as sheet metal, is often required since it is placed with the inner wythe and is subjected to wind with only its inner end supported until the outer wythe is placed. At the same time the flashing must be flexible enough to adjust to the final shelf angle location.

However these considerations are primarily related to the construction process rather than the performance of the completed building and none is so serious as to reduce the desirability of this approach. Therefore the placement of insulation within the cavity is recommended wherever possible.

Figures 4.14 to 4.19 show cavity wall details.

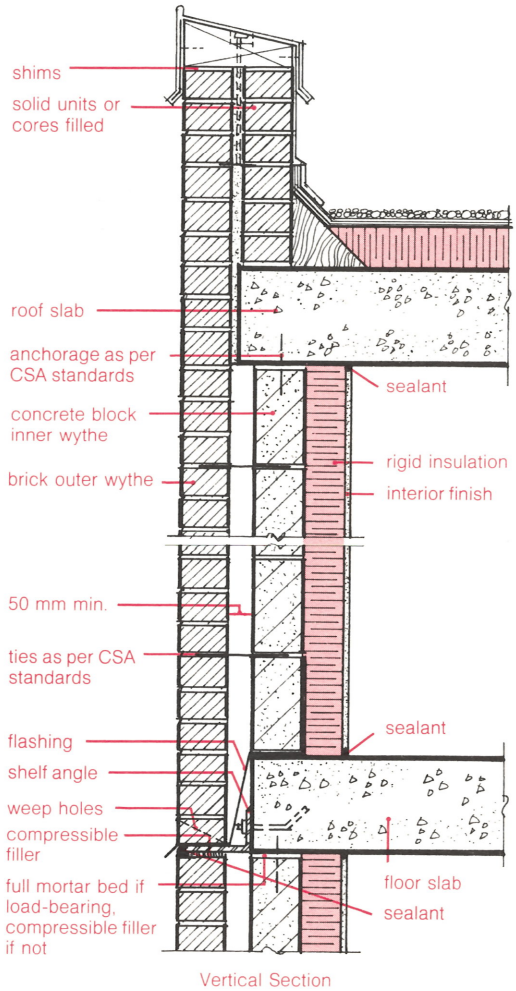


Figure 4.14 Cavity Walls Insulated on Interior. Note Major Thermal Bridges at Slabs. (See text, 2.2.4 regarding disadvantages of interior insulation.)

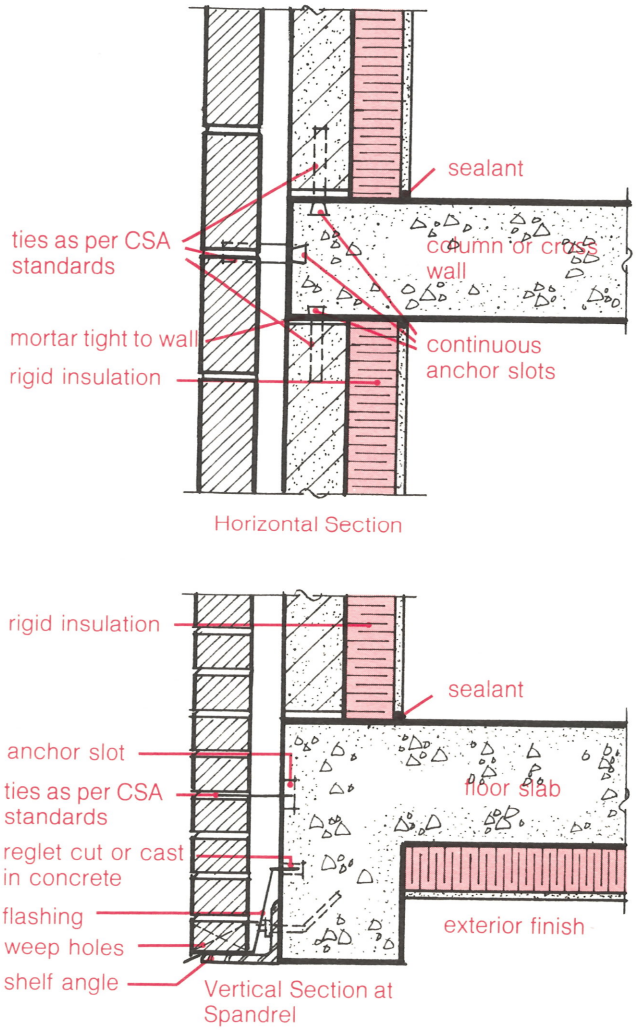


Figure 4.15 Details of Cavity Wall Insulated on Interior. Note Major Thermal Bridges at Spandrel and Column. (See text, 2.2.4 regarding disadvantages of interior insulation.)

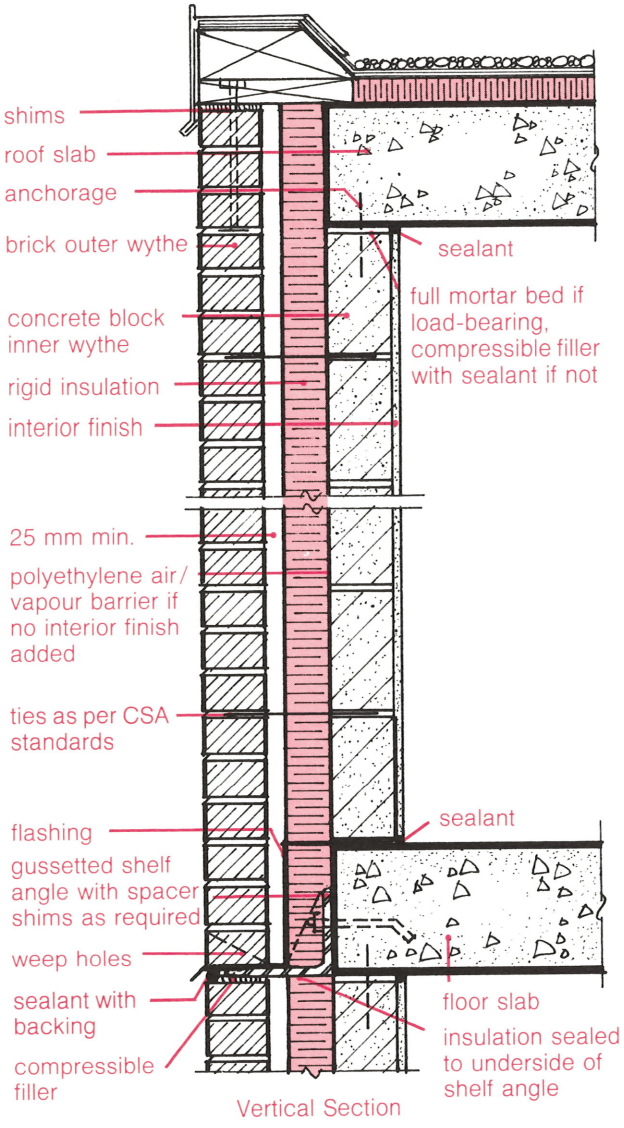
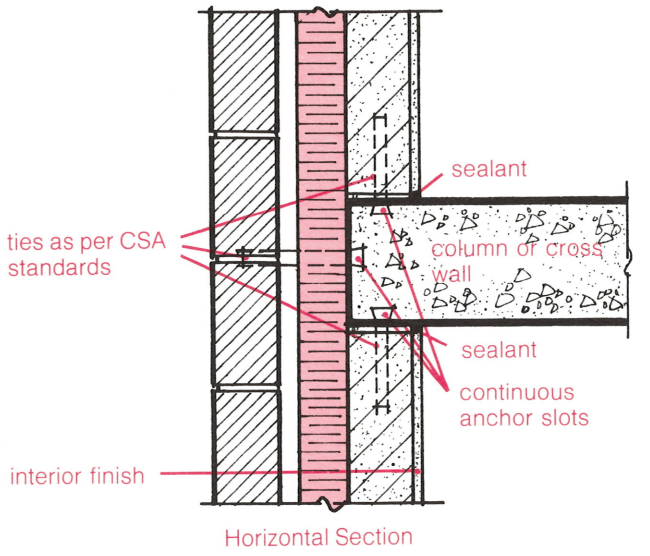


Figure 4.16 Cavity Wall Insulated in Cavity.



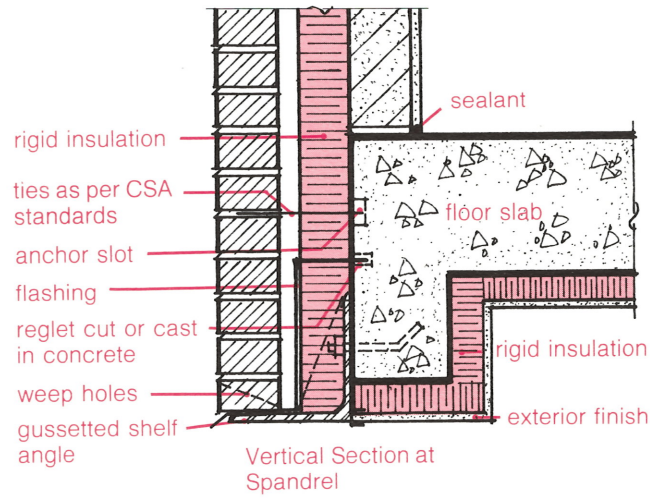


Figure 4.17 Details of Cavity Wall Insulated in Cavity.

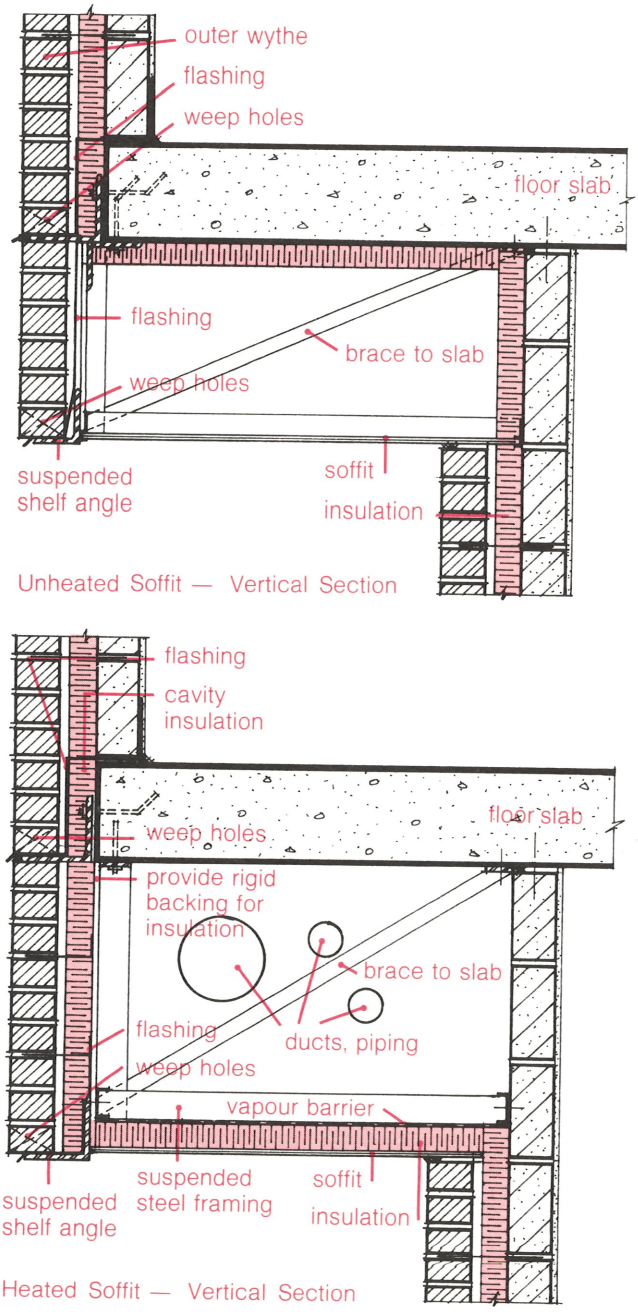


Figure 4.18 Soffit Details — Cavity Wall Insulated in Cavity.

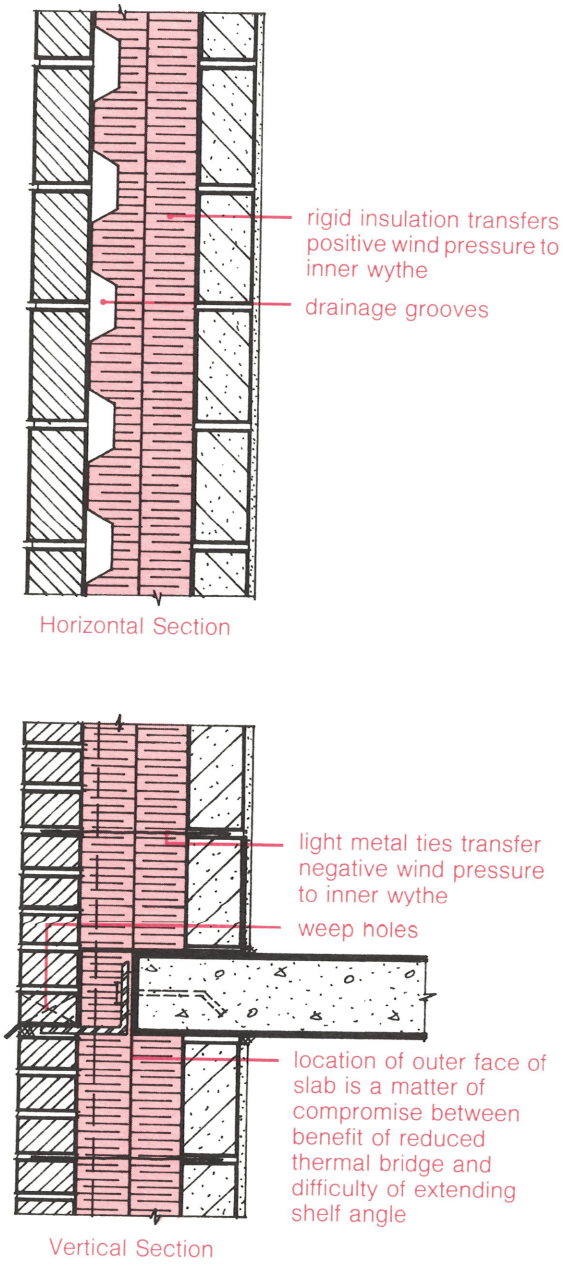


Figure 4.19 Proposed Method of Placing Thick Insulation in Cavity.

4.4.3 Masonry Veneer Walls with Steel* Stud Backing

In concrete or steel frame buildings in which the exterior walls are not required to carry any vertical load the inner masonry wythe of a cavity wall can be replaced with a steel stud framework thus permitting the use of lower cost batt-type insulation (Figures 4.20 and 4.21). Problems have been experienced with this type of construction due to the use of light-gauge interior type studs and inadequate fastening of inadequate masonry ties. These must be designed to resist wind load. Also careful detailing to accommodate shrinkage and other movements of the main building frame is required (9). However if all these considerations are properly taken into account this method will provide acceptable performance, subject to the provisos outlined below.

The steel frame is often assembled and sheathed on the floor then tilted up into position in a manner similar to wood platform frame construction. This requires that clearance be left around the top and sides of each panel. This clearance must be sealed, once the panel is in place, with compressible fillers and sealant.

A water repellant, breather type sheathing paper is applied to the outside of the sheathing after the framework is erected. Its function is to resist rain and wind entry particularly at the joints in the sheathing. It should be applied in horizontal strips with the horizontal and vertical joints lapped at least 100 mm. Its top edge should be bedded in the sealant sealing the top of the panel and its bottom edge should overlap the base flashing or slab.

One disadvantage of this construction is that it incorporates thermal bridges — major thermal bridges at the slabs, spandrel beams and columns or cross-walls and minor thermal bridges in the studs themselves. This latter type of thermal bridge is not so much a concern in terms of heat loss as in the potential for dust marking and condensation on the interior wall surface. However, codes may require that the overall R value of the wall be increased to compensate for this thermal bridging. Both the major and minor thermal bridges can be alleviated by the addition of rigid insulation to the outside of the steel frame either in place of or in addition to the sheathing (Figures 4.22 and 4.23). Although this creates minor difficulties in fitting the insulation around the ties and maintaining the vertical adjustability of the ties, it results in a much better wall and is recommended.

*Much of this Subsection is also applicable to wood stud backing which may be used in buildings where combustible construction is permitted.

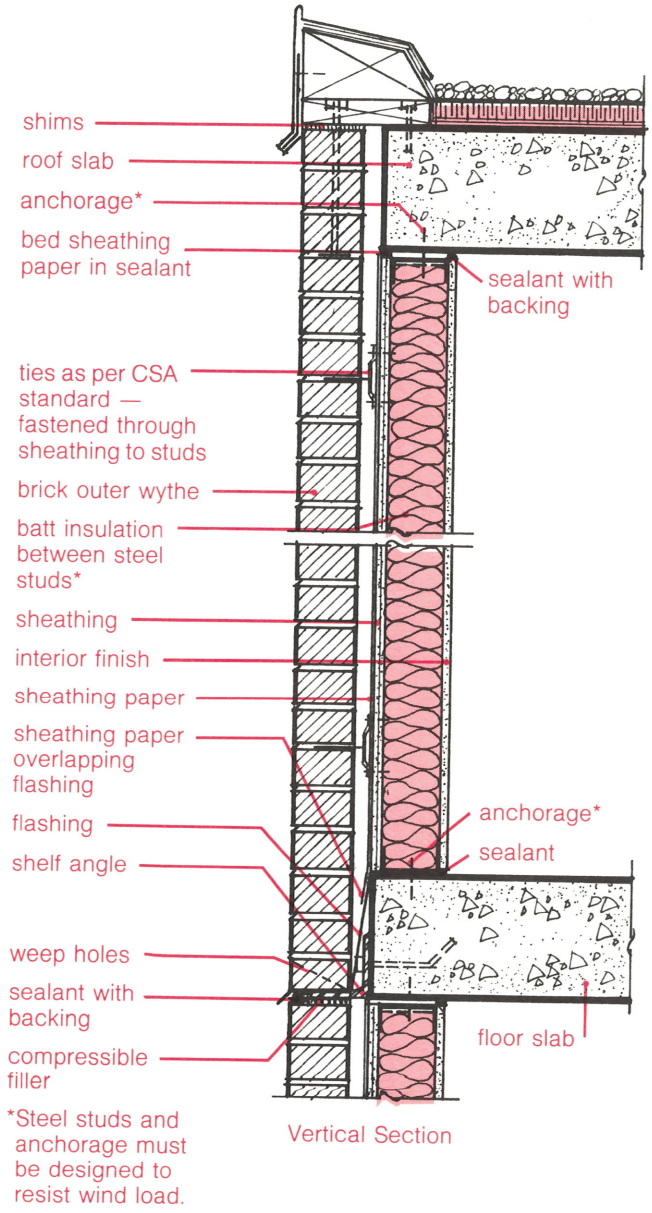


Figure 4.20 Masonry Veneer with Steel Stud Backing. Note Thermal Bridges at Slabs.

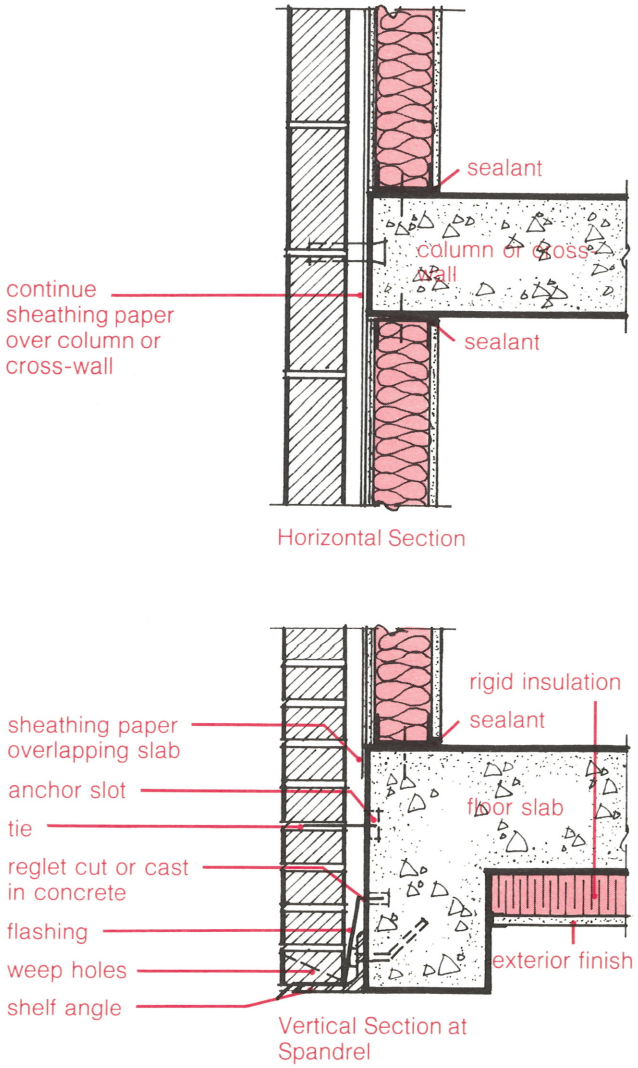


Figure 4.21 Details of Masonry Veneer Wall with Steel Stud Backing. Note Major Thermal Bridges at Slab and Column.

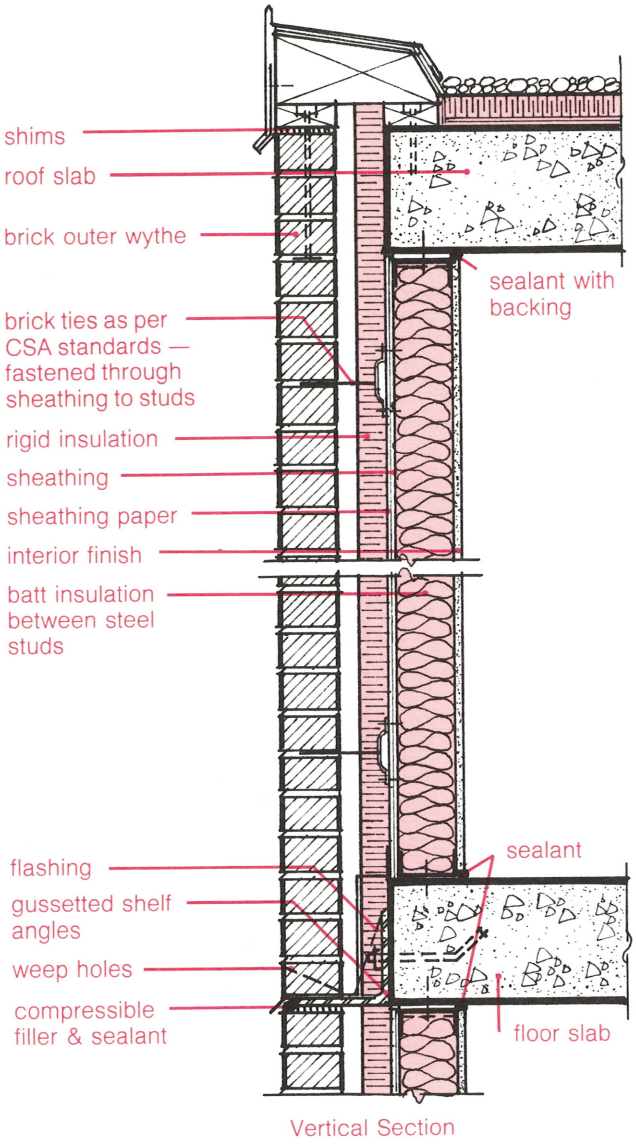


Figure 4.22 Masonry Veneer Wall with Steel Stud Backing and Additional Insulation in Cavity.

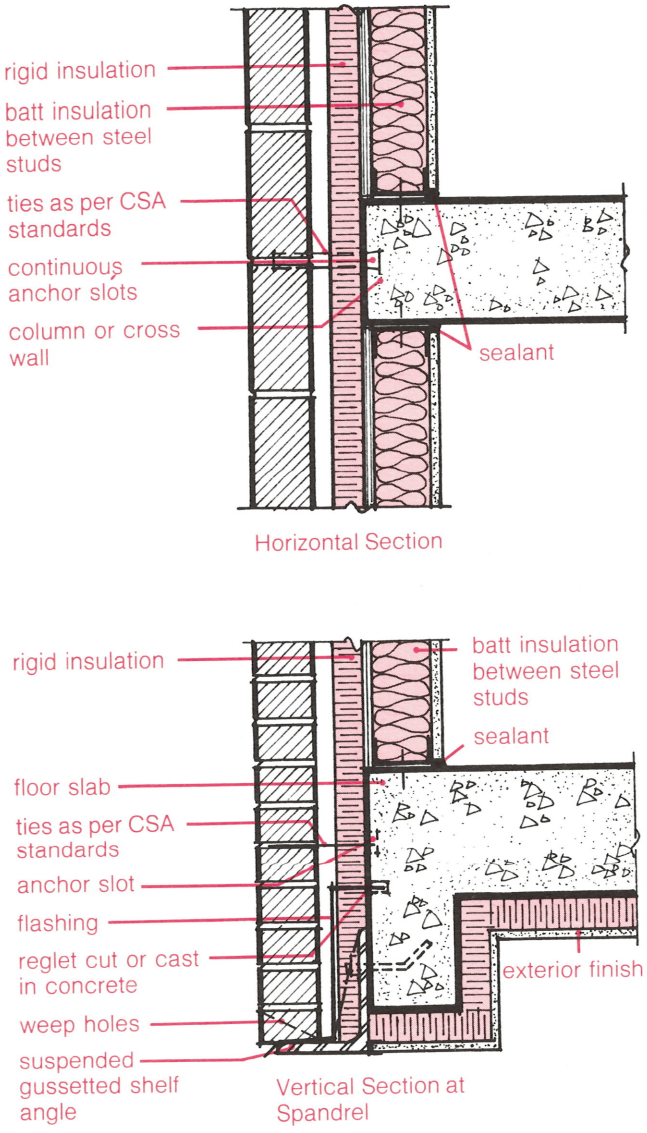


Figure 4.23 Details of Masonry Veneer Walls with Steel Stud Backing and Additional Insulation in Cavity.

4.4.4 Masonry Walls With Insulation-Filled Cavities or Cores

It is not uncommon to fill the cavities of cavity walls and the cores of single wythe block walls with a loose fill type of insulation, usually asphalt-treated vermiculite. Although this method has been used successfully in some circumstances, it cannot be recommended without reservation for the following reasons:

— A cavity wall is usually chosen for its superior resistance to rain penetration. Filling the cavity with any material could potentially block the drainage which the cavity is intended to provide and, if the material is not a type which freely drains, some of the water may be held within the cavity with resulting reduction in thermal resistance and potential freeze-thaw damage to adjacent materials.

— Filling the cores of hollow concrete blocks does not result in a very large absolute increase in thermal resistance due to the extensive thermal bridging by the webs; i.e. the increase may not be commensurate with the cost. The considerations outlined above regarding drainage and water retention would also apply to single wythe block walls.

4.4.5 Single Wythe Precast Concrete Walls

There is a wide variety of ways in which precast concrete can be used in exterior walls. For simplicity the details in this Subsection show it only as a cladding which transmits wind load to the main building structure but carries no vertical load. However the principles illustrated (and discussed below) generally apply to load-bearing precast walls. One exception to this is the fact that major thermal bridges at the floors and roof are unavoidable with single wythe load-bearing precast walls due to the bearing areas required for transfer of floor and roof loads into the walls. This suggests that sandwich panels (see next Subsection) are the preferable method for using precast concrete in load-bearing walls.

It is also apparent that the principles and details dealt with in this Subsection will apply equally to tilt-up construction, which is on-site precast construction, and many would apply to cast-in-place concrete construction.

Where precast cladding is applied over a previously erected wall, as would be the case with a load-bearing masonry wall (Figures 4.25, 4.26 and 4.27) or a concrete end shear wall, it is necessary to leave holes in such walls for access to the hanger connection points for the precast panels. Care must be taken in making these holes good after the precast panels are installed in order to maintain the integrity of the envelope's airtightness and thermal resistance. The thermal consideration is especially true where the insulation is installed on the outer surface of the inner wall prior to erection of the precast panels (Figure 4.26), as is recommended in order to avoid thermal bridges at the slabs. One solution is to fill around the panel connections with pre-packaged foam-in-place urethane. The effect of these holes on the envelope's airtightness will be less of a concern where the approach recommended in Subsection 2.3.2 of treating the interior finish as the primary air barrier is adopted. This is not to suggest that the holes should not be made good when this approach is adopted. They also represent weaknesses in the wall's secondary line of defense against rain penetration.

Figure 4.24 shows different types of joint treatments used with precast panels. The two stage or rainscreen joint is preferable (see Subsection 2.4.2) but is sometimes difficult to achieve. For example, where precast panels are applied over a previously erected wall (Figures 4.25, 4.26 and 4.27) there will be no access to the back of the panel joints. Thus two stage joints can only be achieved if factory applied gaskets are used to provide the inner seal.

Access to the back of the panels for sealing the joints is not a problem where the inner wall is erected after the precast panels, as in the examples in Figures 4.28 and 4.29 where the inner wall is a steel stud type, or where there is no inner wall as in Figures 4.30 and 4.31. This, of course, assumes the panel joints are offset from the slabs and cross-walls or exterior columns.

The steel stud approach is shown in Figure 4.28 with a layer of rigid insulation between the precast panels and the studs in addition to the batt insulation between the studs. This both allows higher R values to be achieved and reduces the effect of thermal bridging through the studs. The rigid insulation would be applied to the inner surface of the precast panels after sealing the panel joints and prior to erecting the steel studs.

It is normal to detail the hangers for precast panels to hold the panels somewhat out from the main structure in order to allow for the fact that the slab edges, cross-walls edges and exterior column faces are unlikely to fall perfectly into one plane. The National Building Code of Canada requires that the concealed spaces thus created be fire stopped at each floor level. See Subsection 4.1.4.

For simplicity only one type of hanger connection detail is used throughout the following drawings. It is only one of many possible details. These must be designed for each individual case by the structural engineer or panel supplier.

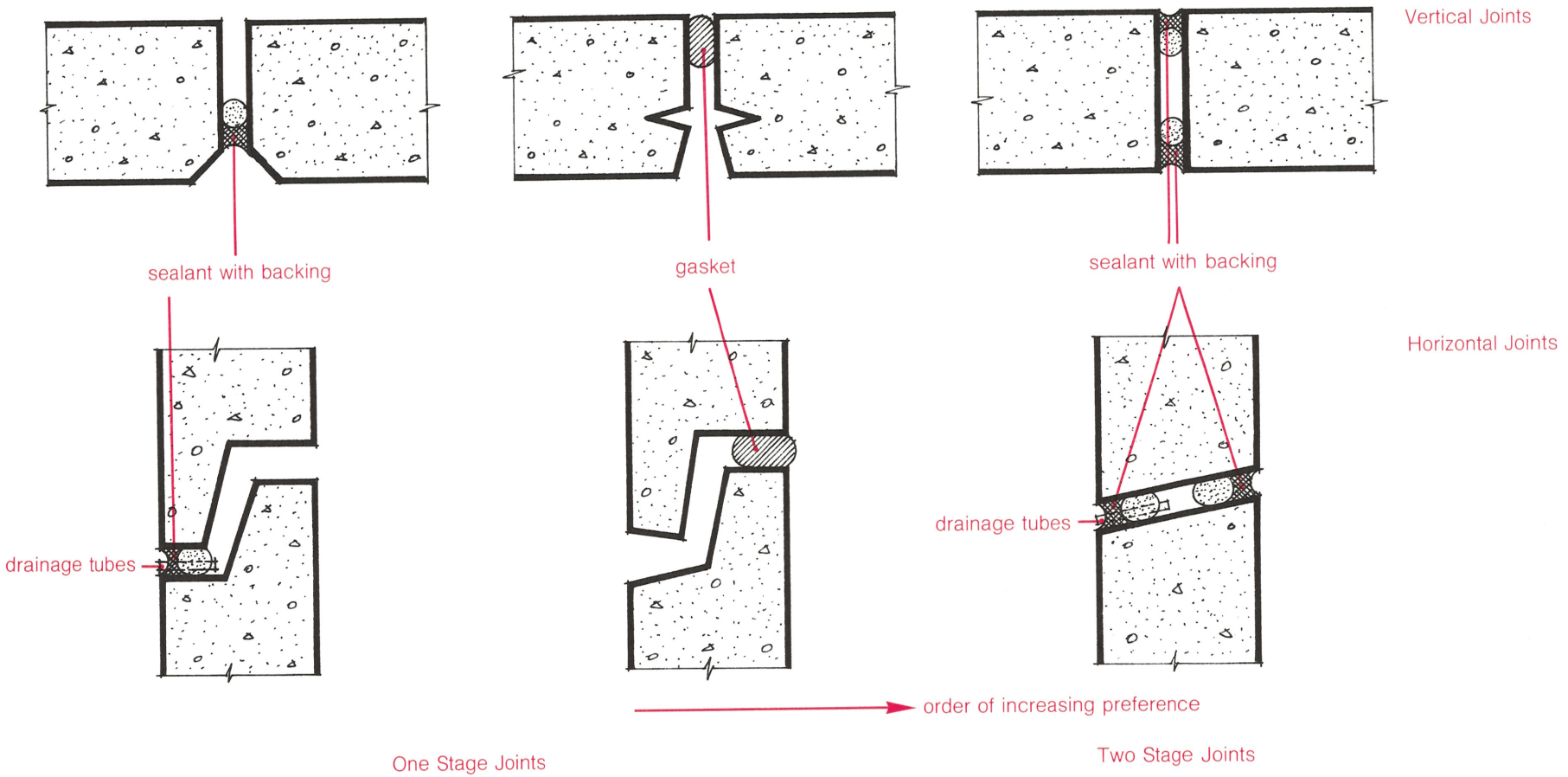


Figure 4.24 Precast Joints
(Interior Surface at Top or Right)

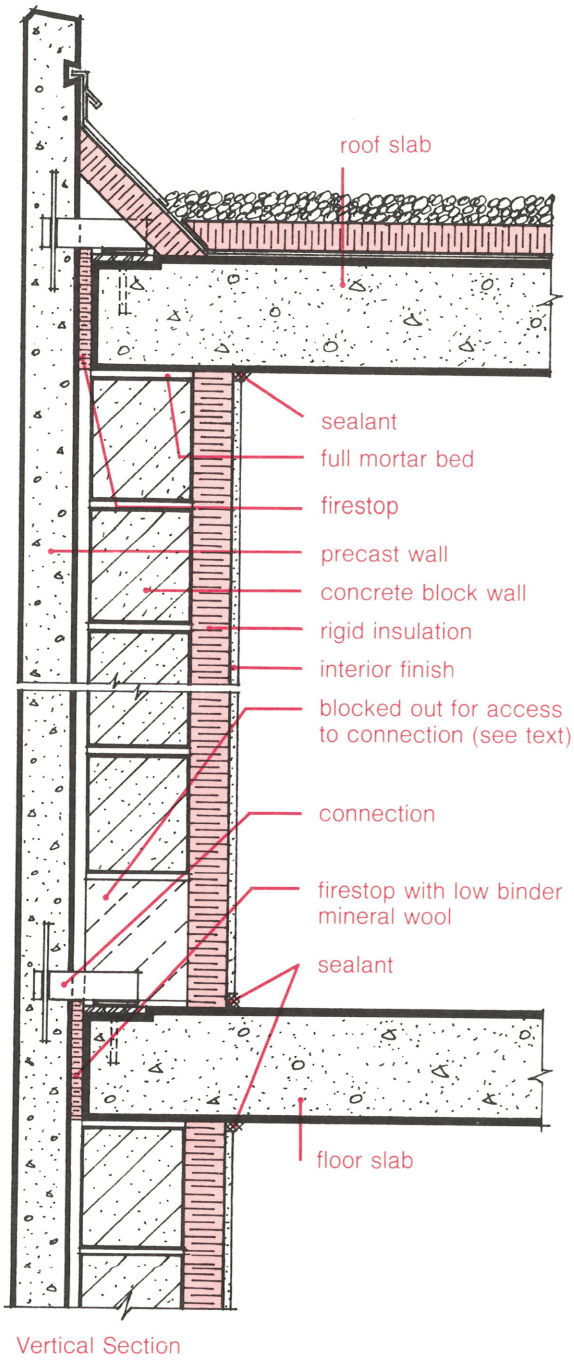


Figure 4.25 Precast Cladding over Masonry Bearing Wall — Insulated on Interior. (See text, 2.2.4, regarding disadvantages of interior insulation.)

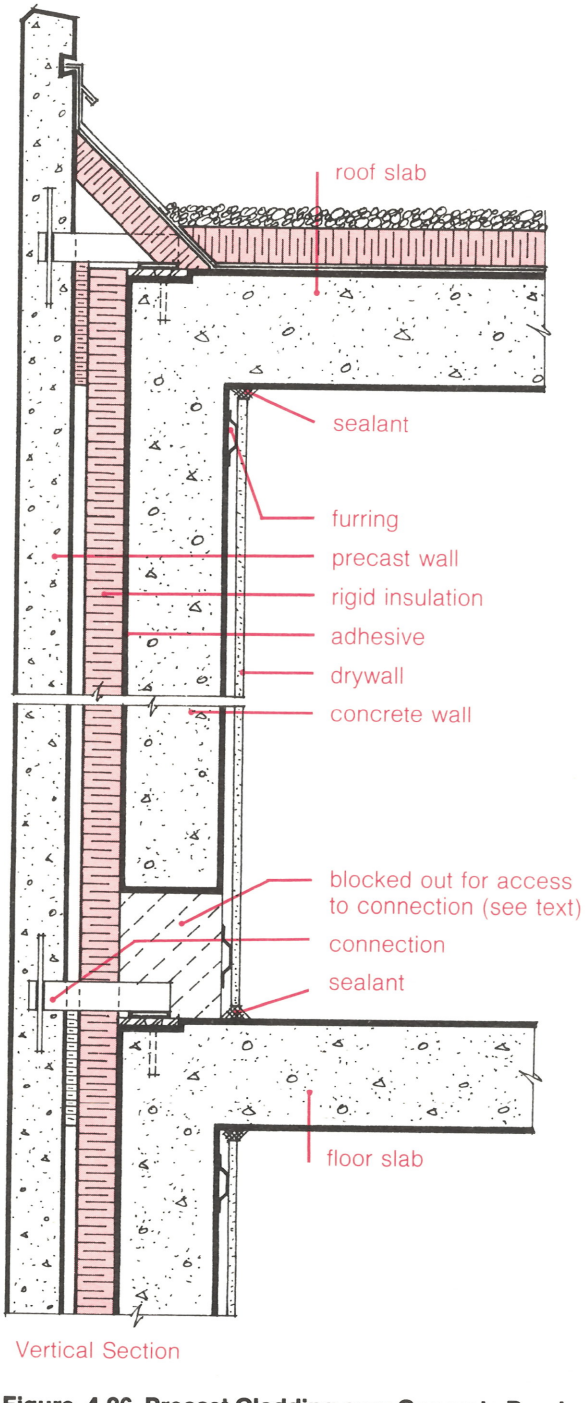
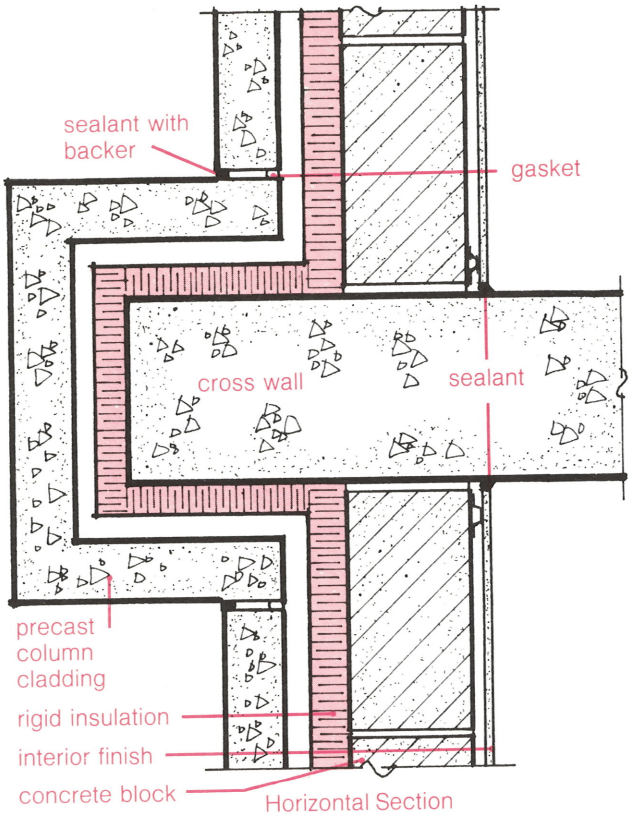


Figure 4.26 Precast Cladding over Concrete Bearing Wall — Insulated in Cavity.



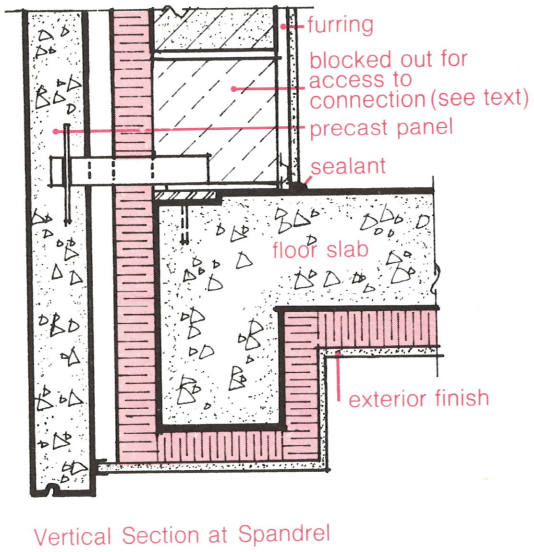
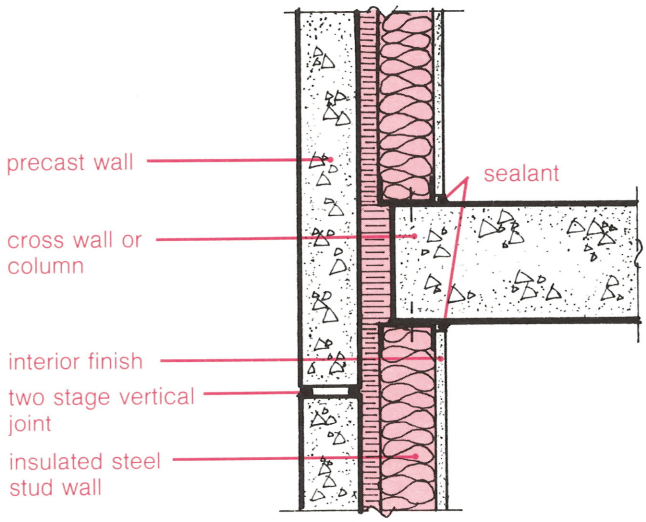


Figure 4.27 Details of Precast Cladding over Masonry Bearing Wall.



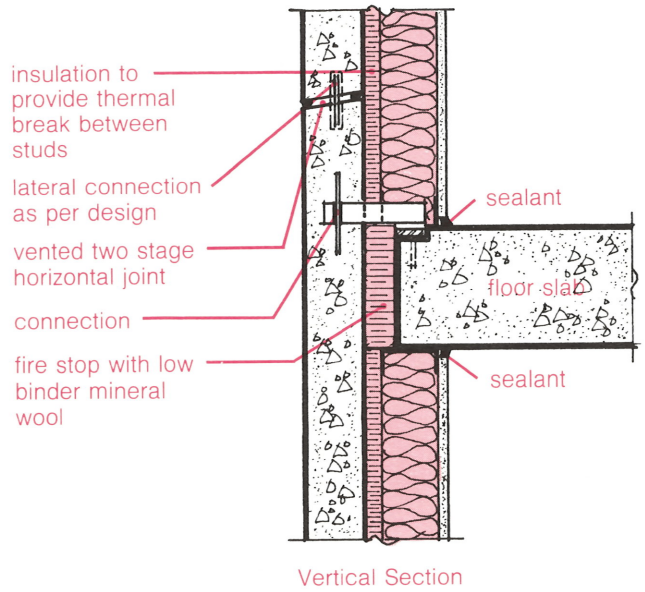


Figure 4.28 Precast Wall with Steel Stud Backing.

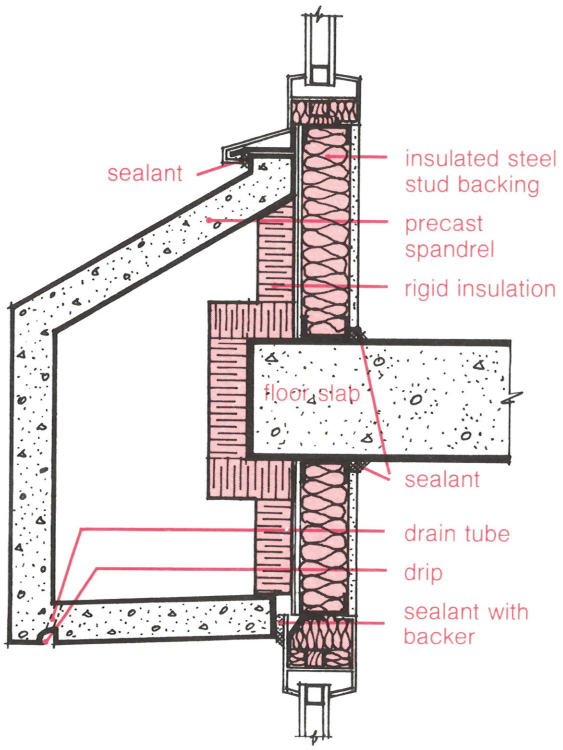
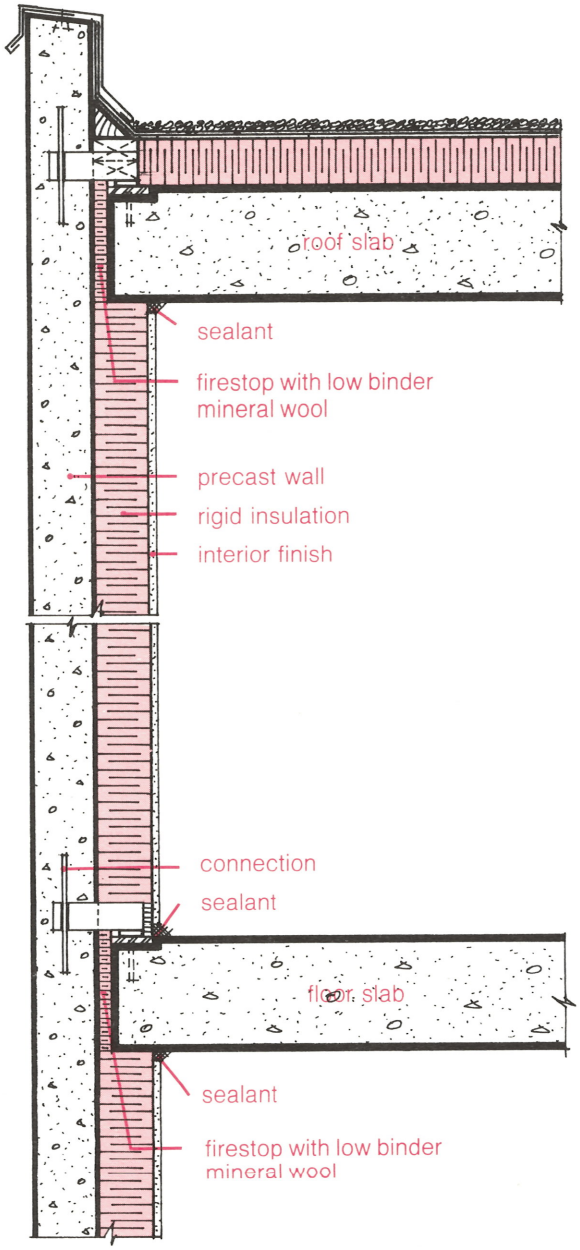
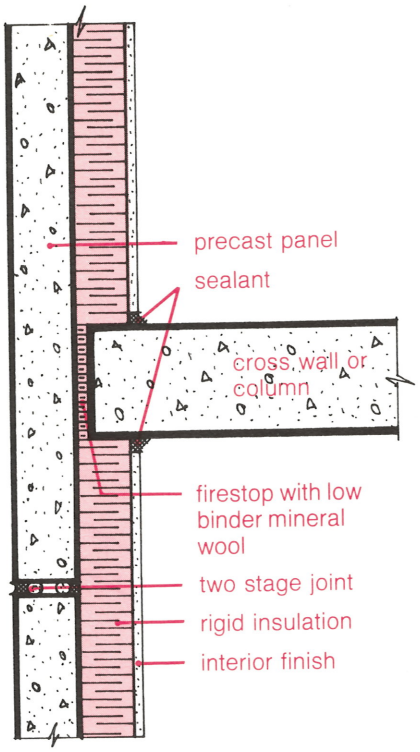


Figure 4.29 Precast Spandrel Panel with Steel Stud Backing.

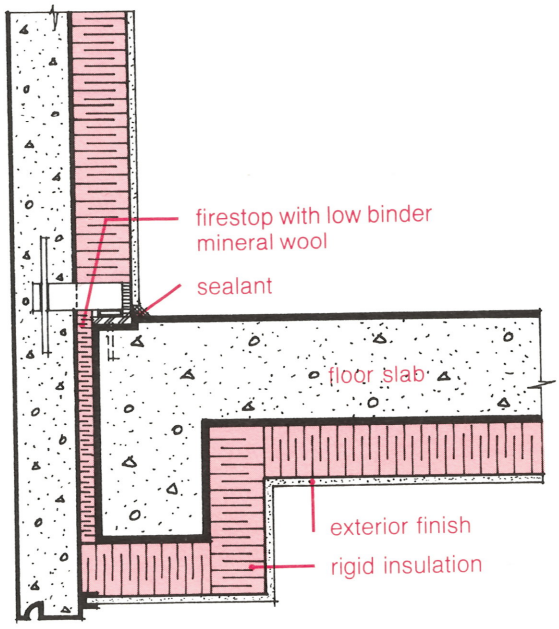


Vertical Section

Figure 4.30 Precast or Cast-in-place Wall Insulated Directly.



Horizontal Section



Vertical Section at Spandrel

Figure 4.31 Details of Precast or Cast-in-place Wall Insulated Directly.

4.4.6 Precast Concrete Sandwich Panels

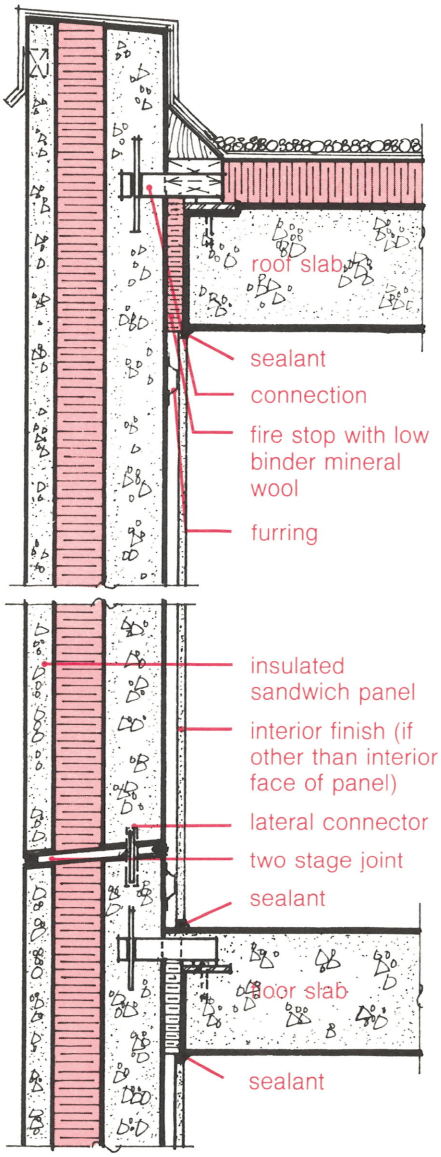
There are two basic types of precast concrete sandwich panels — composite and non-composite. The difference between them is that the composite type has stiffer connections between the inner and outer wythes in order that the two wythes will act jointly in resisting load. This permits a net reduction in their thickness. However this rigid connection means that the two wythes will also react jointly to stimuli other than applied load. For example, when the outer wythe is subjected to a temperature drop, it will not contract independently but the whole panel will tend to bow inwards. For this reason non-composite panels are preferable in high R value walls, where the outer wythe is likely to be subject to large temperature swings. Non-composite panels will also have less thermal bridging through the wythe connections. To ensure that the insulation does not transfer shear between the wythes and thus result in some degree of composite action, two layers should be used and/or some means of preventing a bond between the insulation and one of the wythes should be used. This bond-breaker can be in the form of a polyethylene or paper film or a release oil sprayed on the surface of the insulation before the top wythe is cast.

The insulation used in sandwich panels must be a type with low water absorption in order that it will not draw water out of the curing concrete. Alternatively its surface can be coated to prevent this. A bond-breaker treatment may accomplish this as well. In order to reduce local cold spots at insulation joints, sheets as large as possible should be used and, where two layers are used, the joints should be staggered.

Considerations regarding joints between sandwich panels are much the same as for single wythe precast panels with the added concern that sandwich panels are sometimes used without a separate interior finish. This means that the inner wythe and the inner joint seal make up the air barrier. The integrity of this seal is thus doubly important.

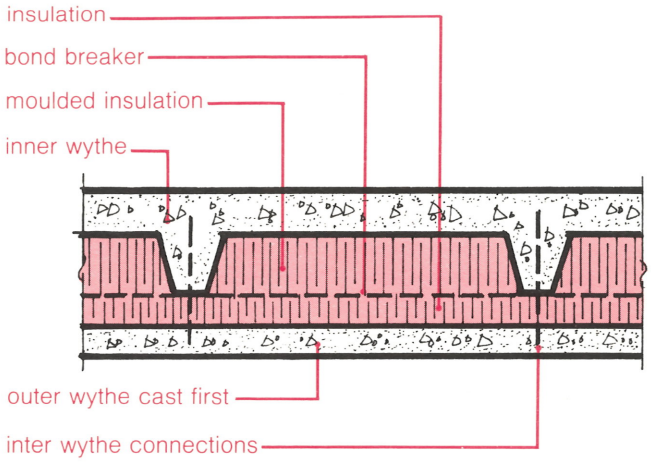
Sandwich panel walls also require firestopping at floor levels (see discussion in previous Subsection). However there is no need for the firestop material to have any particular thermal properties since there is no potential thermal bridging problem.

Figure 4.32 shows typical sandwich panel installation details. Figure 4.33 shows a proposed approach to the casting of high R value sandwich panels without the inter-wythe connections becoming too slender.



Vertical Section

Figure 4.32 Precast Sandwich Panel



Vertical Section in Casting Bed

Figure 4.33 Possible Approach to Casting High R Value Sandwich Panels.

4.5 Insulating Roofs

There are a number of approaches to the insulation of concrete roof decks which one might consider. The first choice which must be made is whether to insulate below or above the deck.

Insulation can be applied directly to the underside of the roof deck using the "stick clip" or furring techniques discussed in Subsection 4.2. It can also be installed in a ceiling suspended under the roof deck as discussed for floors in Subsection 4.3.1. The concerns and difficulties outlined in Subsection 4.3.1 regarding the use of this latter technique with floors apply equally well to roofs except that the danger is that the ceiling will be penetrated by warm interior air rather than cold outside air. This is even more serious a concern with roofs than floors since such penetration results not only in short circuiting of the insulation but also in condensation of water vapour.

No matter what technique is used to apply insulation below the roof deck, the results are the same in the following ways:

— Major thermal bridges are unavoidable at the supporting walls or columns,

— the deck is subjected to large temperature variations with resulting thermal movement, and

— the mass of the deck is not able to participate effectively in the storage of surplus internal heat gains,

all as discussed in Subsection 2.2.4. Other disadvantages of this approach include the difficulties of cutting and fitting the insulation and any separate air/vapour barrier around walls, columns and other interruptions and the danger of trapping moisture between an intentional vapour barrier and the unintentional vapour barrier created by the roof membrane.

Thus insulating above the roof deck while not without problems, is the preferable method. Within this method there are three approaches to location of the roofing membrane:

— In the conventional roof, the membrane is located on top of the insulation (Figure 4.34 A).

— In the protected membrane roof assembly the membrane is placed below the insulation (Figure 4.34 B).

— It is also possible to combine the above two approaches and locate the membrane in the middle of the insulation (Figure 4.34 C).

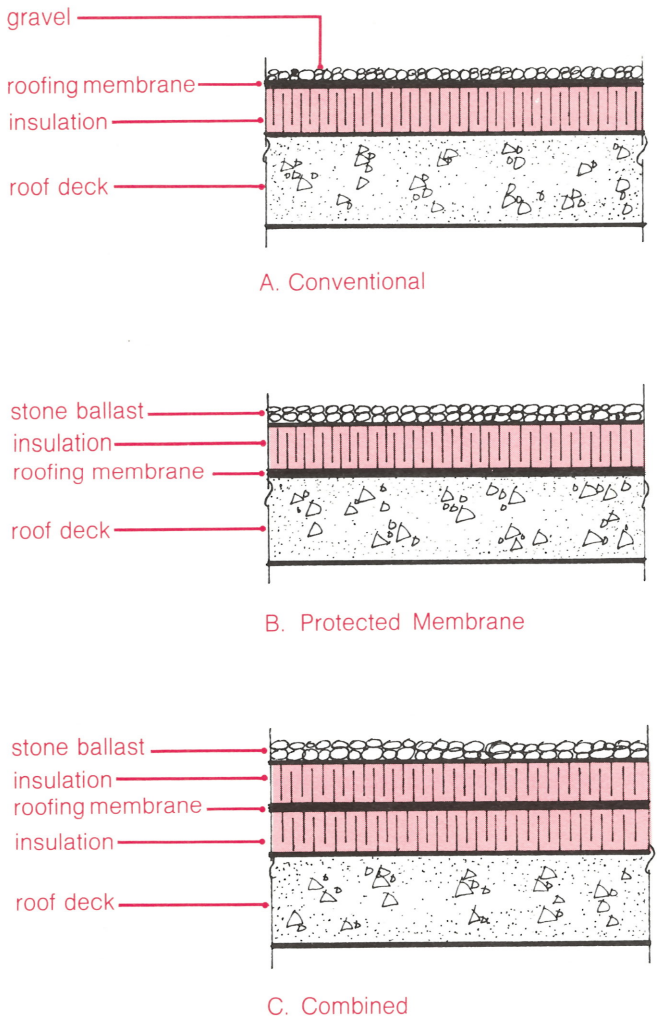


Figure 4.34 Three Approaches to Insulating above the Roof Deck.

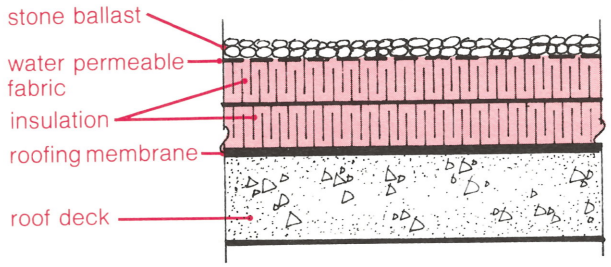


Figure 4.35 Modified Inverted Roof Membrane Assembly.

Subsection 2.4.1 outlined the problems that can occur as a result of thermal expansion and contraction of insulation when the membrane is placed above the insulation. The data on thermal expansion properties of various insulations in Subsection 4.1.1 will help in choosing materials to minimize these problems.

Subsection 2.4.1 also outlined the advantages of the protected membrane approach in avoiding the above problems and in protecting the roofing membrane from extreme temperature changes and the ultraviolet rays of the sun. However, in designing such inverted roofs it is usually assumed that the relationship between the rate of rainfall and the capacity of the roof drains will be such that water will temporarily accumulate to the full depth of the insulation and thus sufficient stone ballast must be placed on top of the insulation to prevent its flotation. As the thickness of the insulation is increased, the weight of the ballast must be increased and this, of course, represents an increase in the design load on the roof. One alternative to simply adding more ballast is to cover the top of the insulation with a water permeable fabric (Figure 4.35). This allows the insulation to float in localized areas where the water accumulation is greatest (usually around roof drains) without its joints separating or the ballast falling through the joints. This approach is recommended where the insulation thickness exceeds 50 mm.

Another alternative is to place some of the insulation below the membrane and some above. This partially defeats one of the objectives of the protected membrane approach since the membrane will now be subjected to somewhat greater temperature variations (although not as great as in a conventional roof). This suggests that as much of the insulation as possible should be placed above the membrane, consistent with the need to avoid excessive ballast.

Any insulation placed above the roofing membrane in either the protected membrane or combined approaches should be a type with good resistance to moisture absorption. Extruded polystyrene is the most widely used type for this application.

Ribbed roof slabs present no unusual insulating problems if the insulation is placed above the deck. However there can be thermal bridging and air sealing problems if they are cantilevered, as is not uncommon. Figure 4.36 shows a suggested detail for the end treatment of this type of roof.

Cantilevering any type of roof slab insulated on the exterior will create a major thermal bridge and should be avoided if possible.

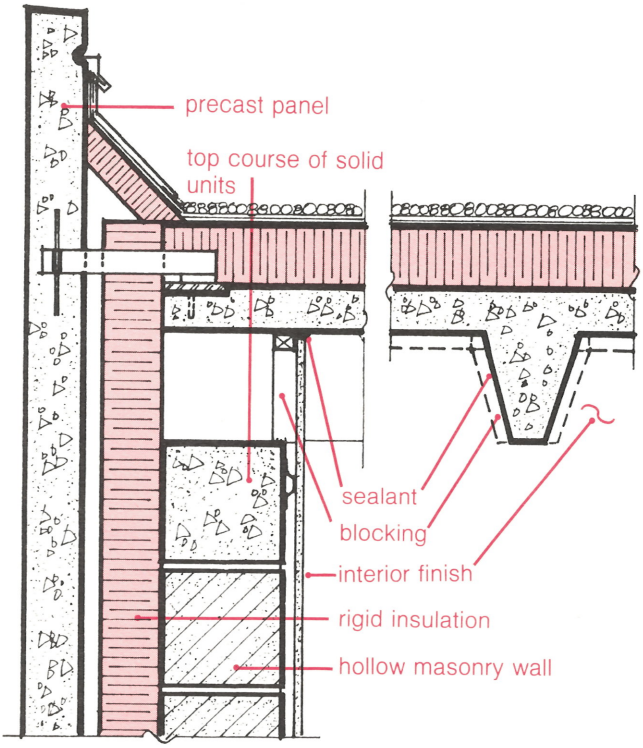


Figure 4.36 End Treatment of Ribbed Roof Slabs.

4.6 Tables of R Values of Insulated Assemblies

The following tables of typical floor, wall and roof assemblies were designed to provide a quick reference for the selection and determination of:

— the uninsulated R value of an assembly;

— the insulated R value of an assembly utilizing various insulation types and thicknesses;

— the insulation type and thickness required to achieve a given total R value.

Assumptions

The values in the tables are based on the following assumptions:

— R values include surface film coefficients, air spaces and finishes.

— 200 mm normal density concrete for floor and roof slabs, concrete backup walls, and precast sections.

— 100 mm clay bricks except where noted.

— 90 mm rectangular core concrete blocks (except where noted) of sand and gravel aggregate and normal density (2100 kg/m^3).

— 100 mm lightweight concrete precast curtain wall panels where concrete or concrete block backup walls are utilized.

— 50 mm topping coats on precast floor assemblies.

How to Use the Tables

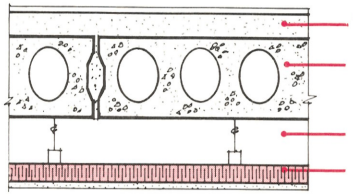
To determine the insulated R value for an assembly, simply select the insulation type, scan down the appropriate column to the desired thickness, and look horizontally across to the R column for the total R value of the assembly.

To select the appropriate insulation type and thickness required to achieve a given total R value, simply reverse the procedure.

R values are in m^2•°C/W

— Assemblies using concrete block of light density (1700 kg/m^3) will have R values approximately 0.1 m^2•°C/W higher than those shown in the tables.

Hollow Core Floor/Suspended Ceiling

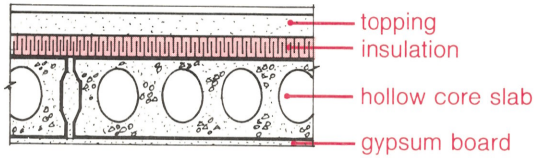


Uninsulated R-0.98

Insulation Type & Thickness mm.

R	mineral fibre batts *(higher density, R2.1 & 2.4)	polystyrene type 2; rigid mineral fibre	polystyrene type 4	polyisocyanurate polyurethane phenolic	R
2.0	70	25 38 50	25 38	29 41 52	2.0
3.0	89 *89 *89	75	50	38	3.0
4.0	150	100 125	75 100	50 75	4.0
5.0					5.0

Hollow Core Floor/Insulated Above

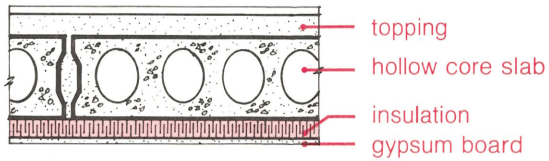


Uninsulated R-0.69

Insulation Type & Thickness mm.

R	polystyrene type 2; rigid mineral fibre	polystyrene type 4	polyisocyanurate polyurethane phenolic	R
2.0	25 38 50	25 38	29 41 52	2.0
3.0	75	50	38	3.0
4.0	100 125	75 100	50 75	4.0
5.0				5.0

Hollow Core Floor/Insulated on Underside

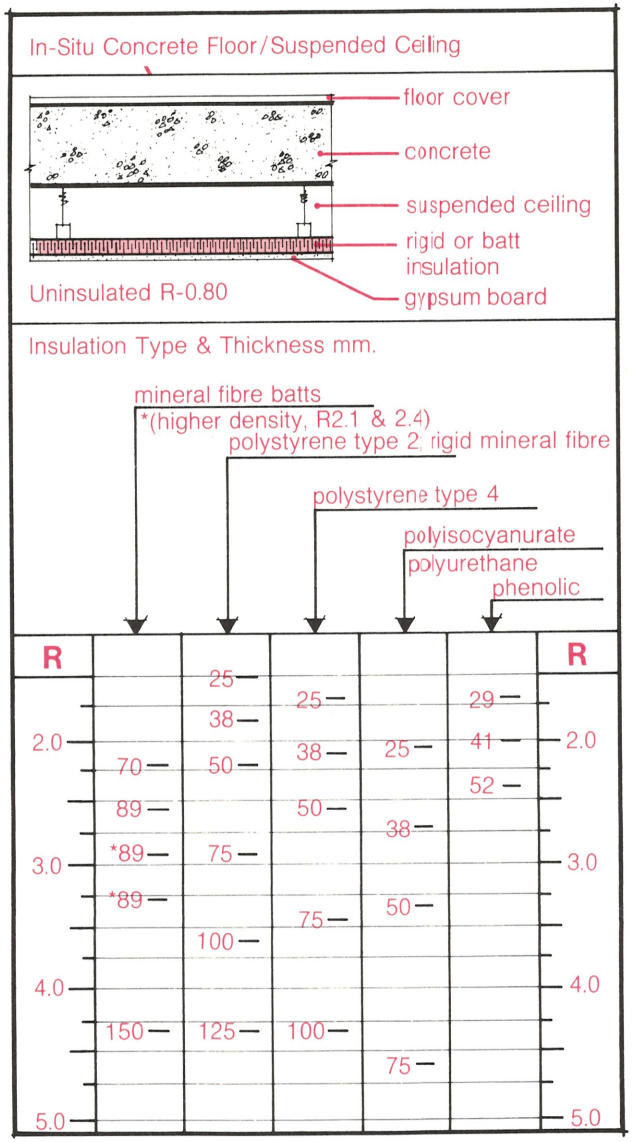


Uninsulated R-0.79

Insulation Type & Thickness mm.

R	polystyrene type 2; rigid mineral fibre	polystyrene type 4	polyisocyanurate polyurethane phenolic	R
2.0	25 38 50	25 38	29 41 52	2.0
3.0	75	50	38	3.0
4.0	100 125	75 100	50 75	4.0
5.0				5.0

Table 4.6A Hollow-Core Slab Floors



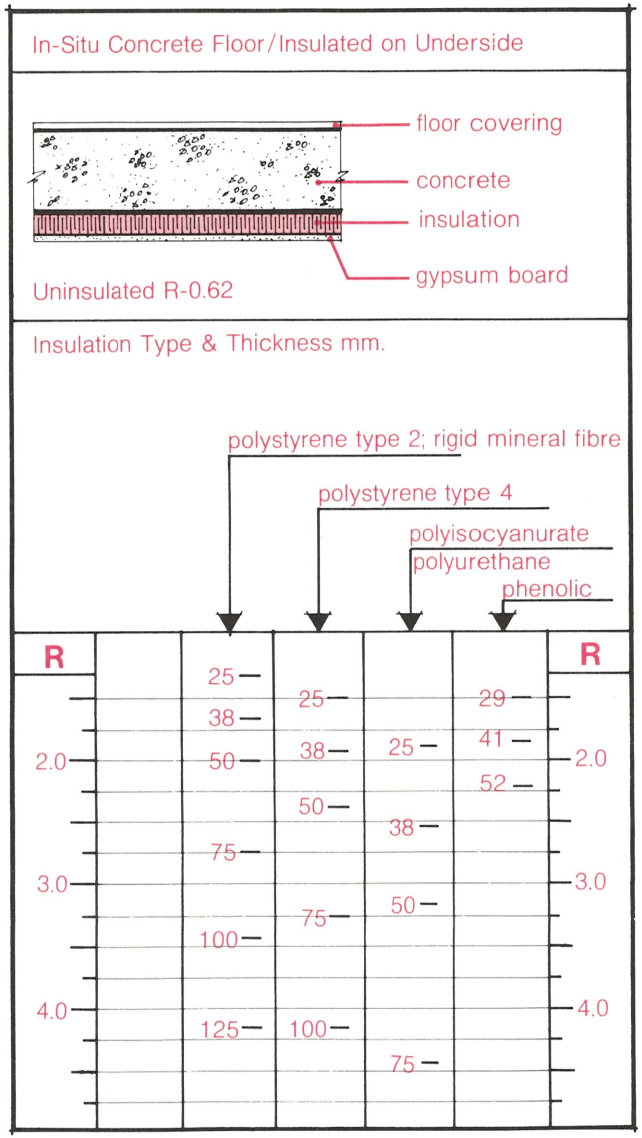


Table 4.6B In-Situ Concrete Floors

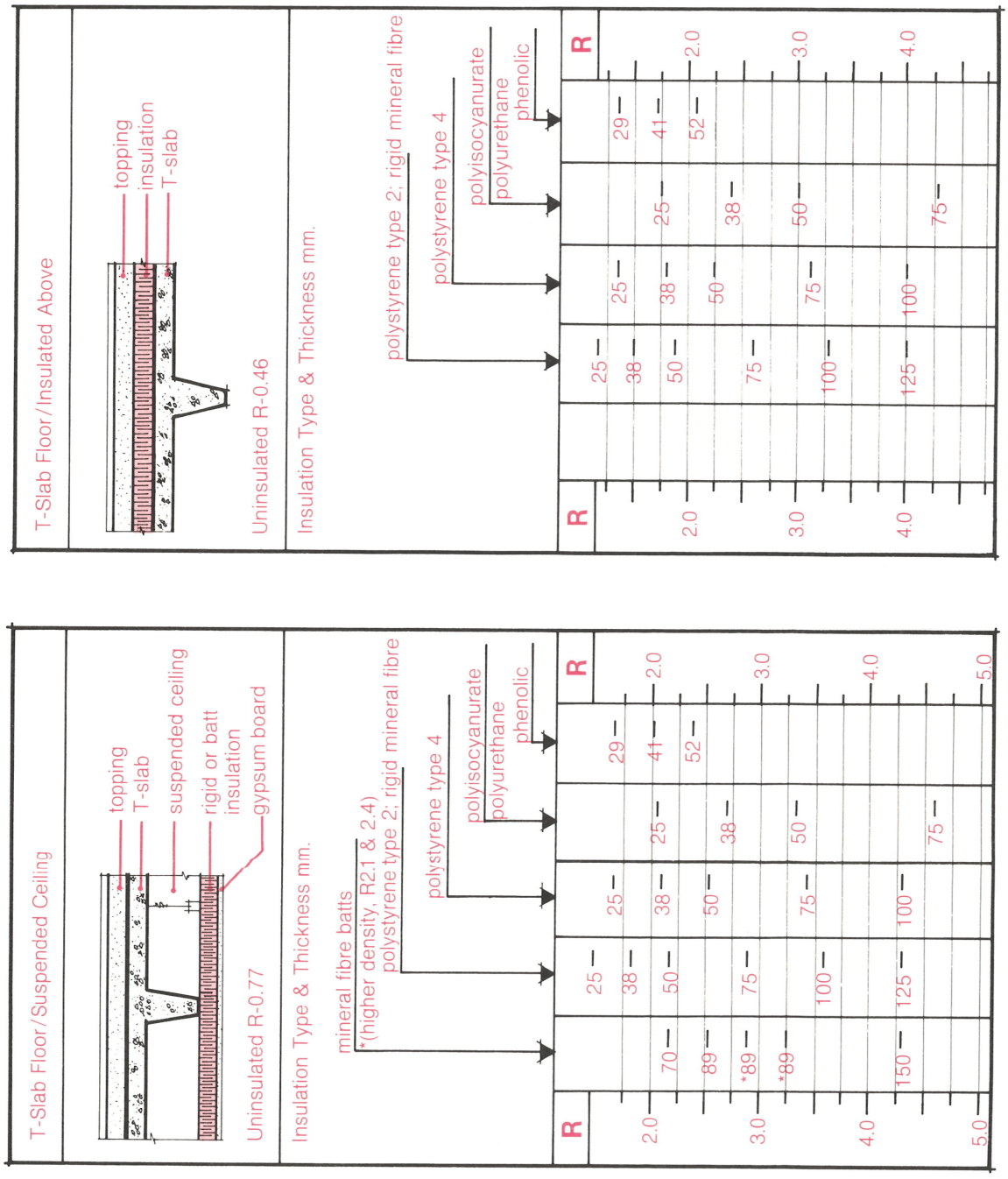
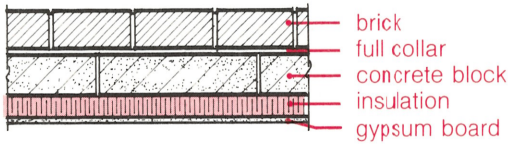


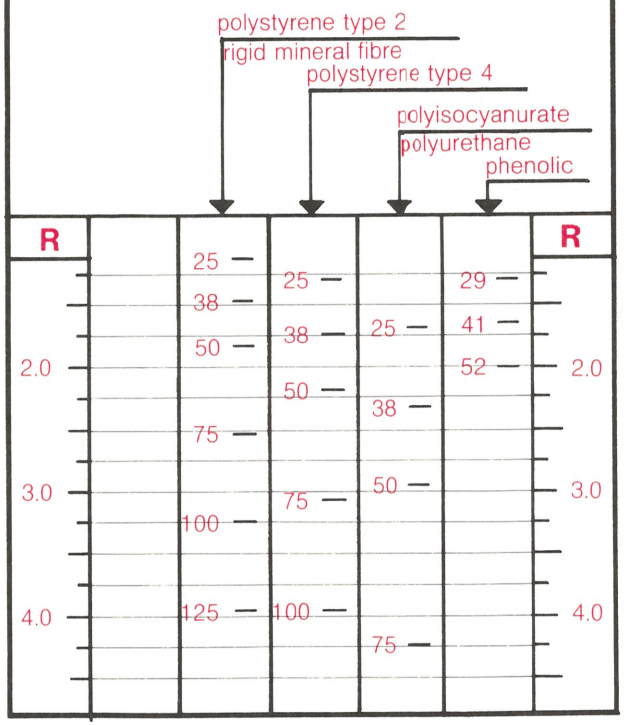
Table 4.6C T-Slab Floors

Solid Masonry Wall/Interior Insulation

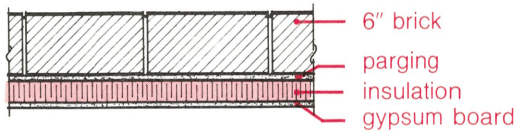


Uninsulated R-0.49

Insulation Type & Thickness mm.

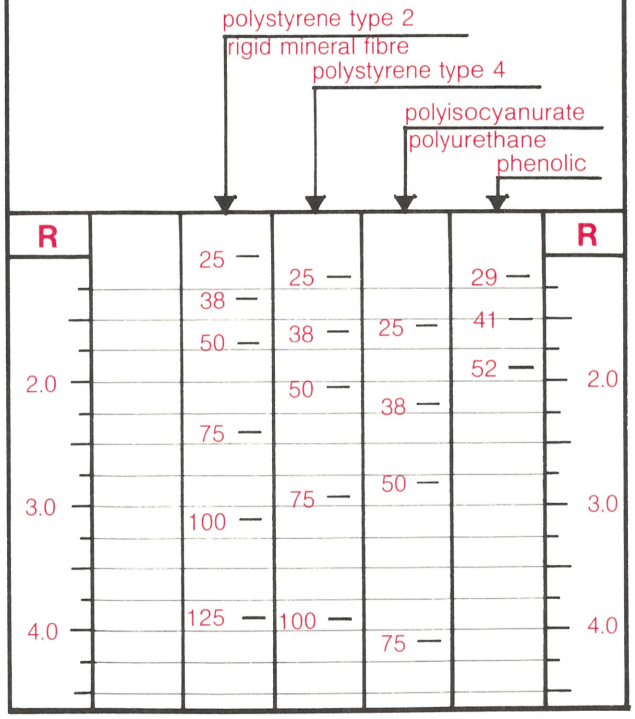


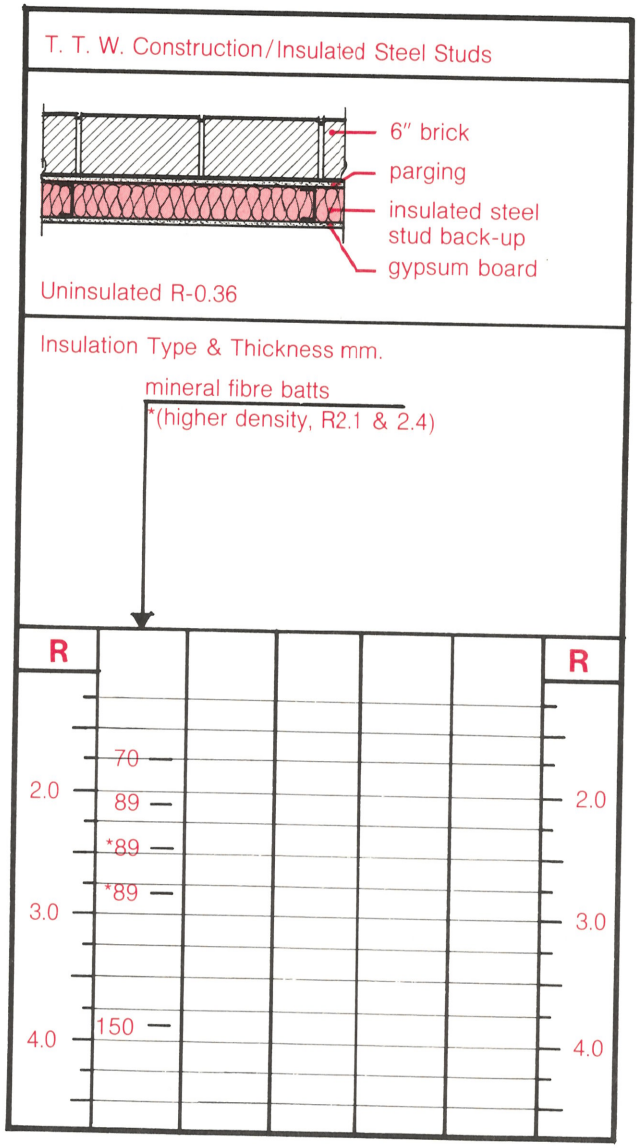
T. T. W. Construction/Interior Insulation



Uninsulated R-0.35

Insulation Type & Thickness mm.





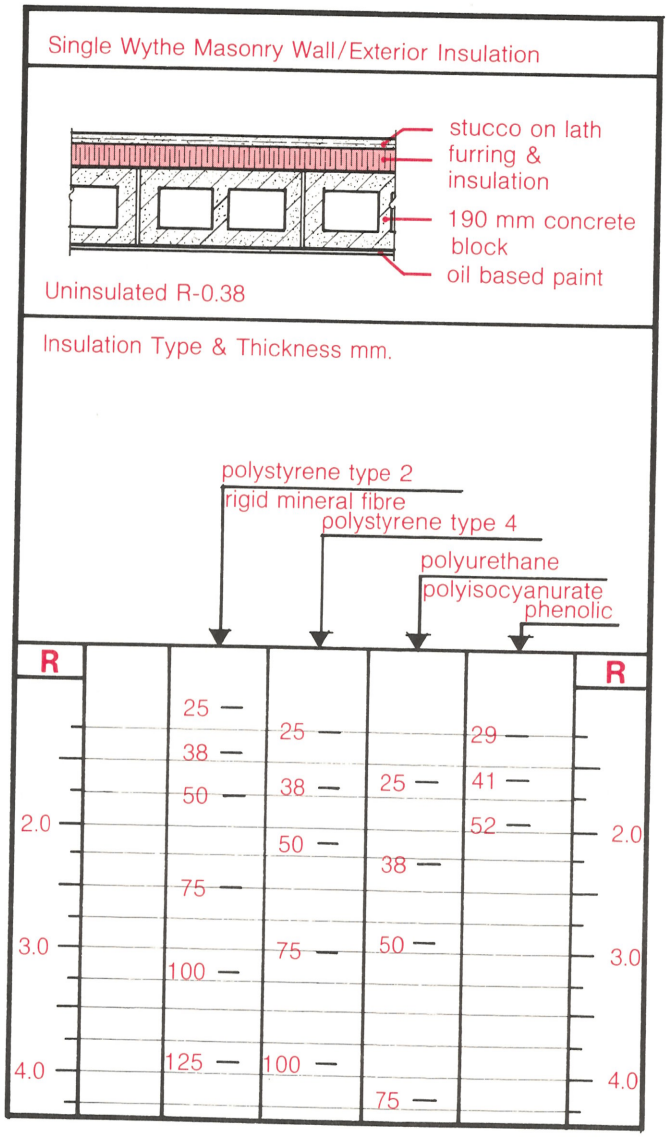
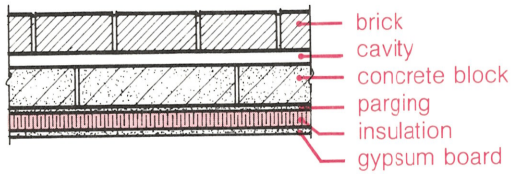


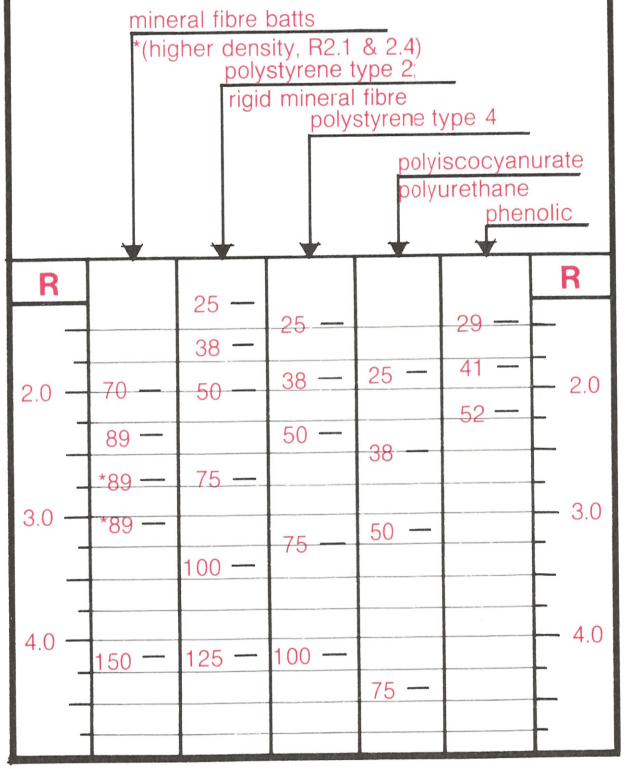
Table 4.6D Solid Masonry Walls

Masonry Cavity Wall/Interior Insulation

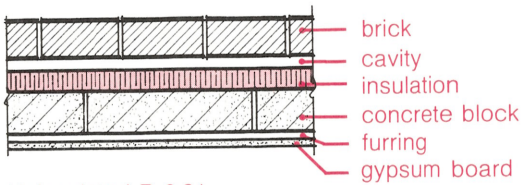


Uninsulated R-0.65

Insulation Type & Thickness mm.

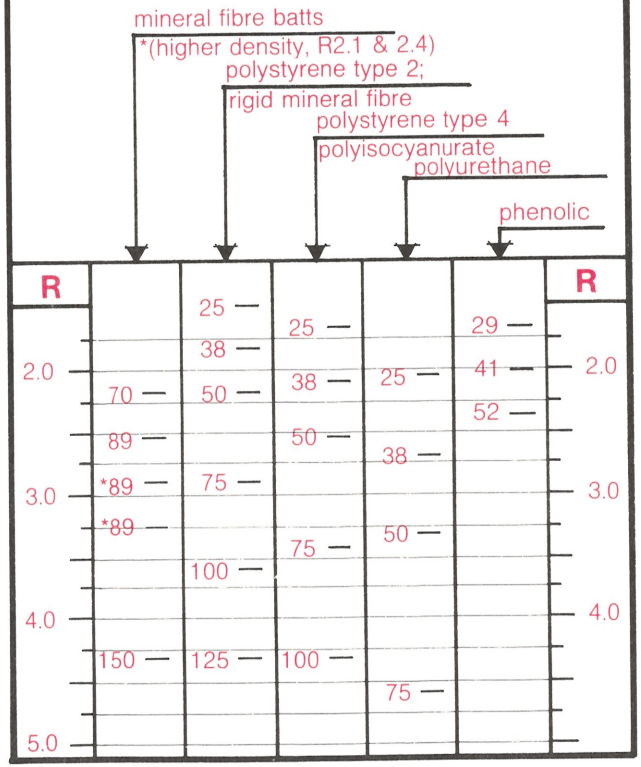


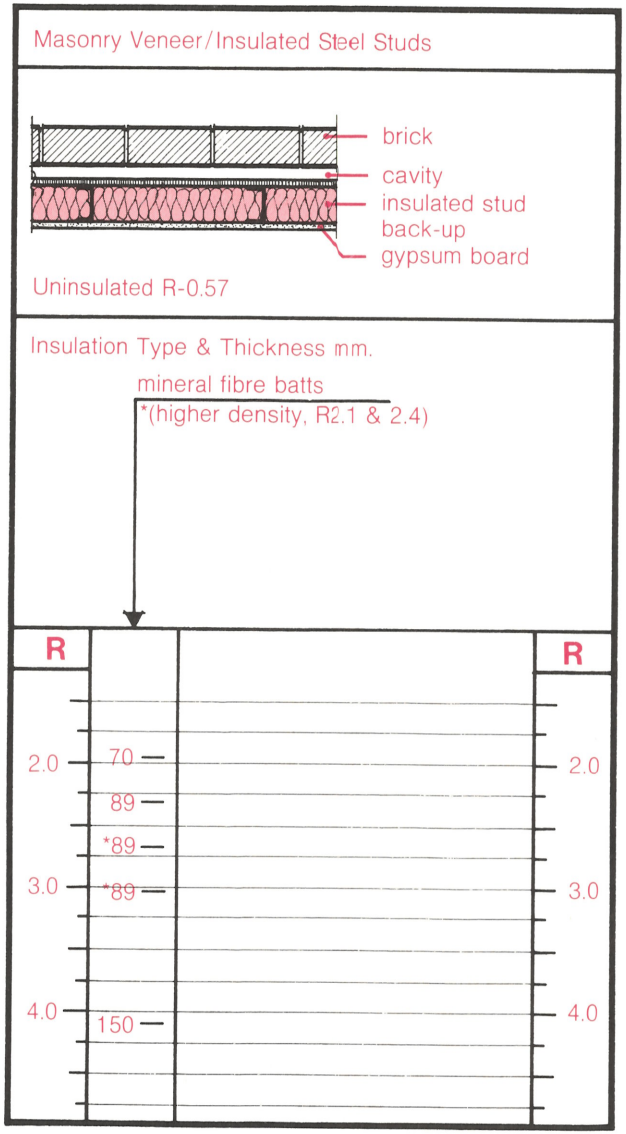
Masonry Cavity Wall/Cavity Insulation



Uninsulated R-0.81

Insulation Type & Thickness mm





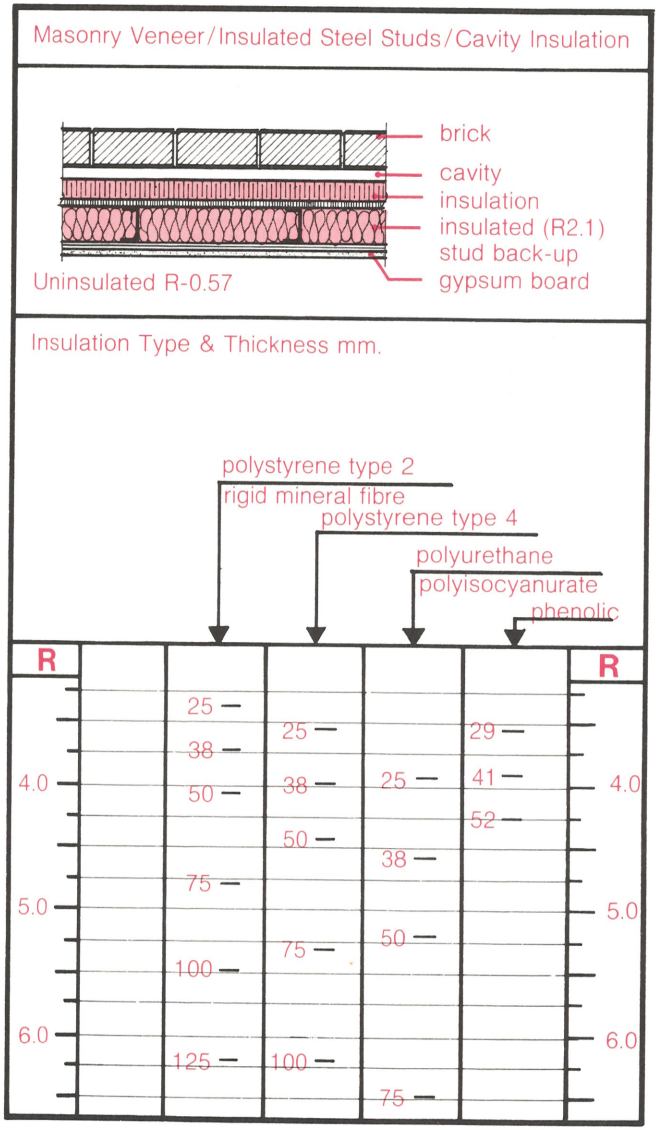
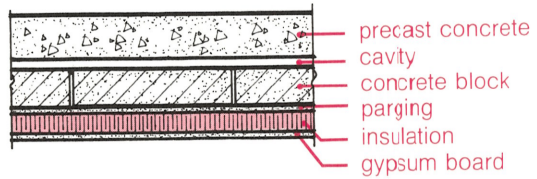


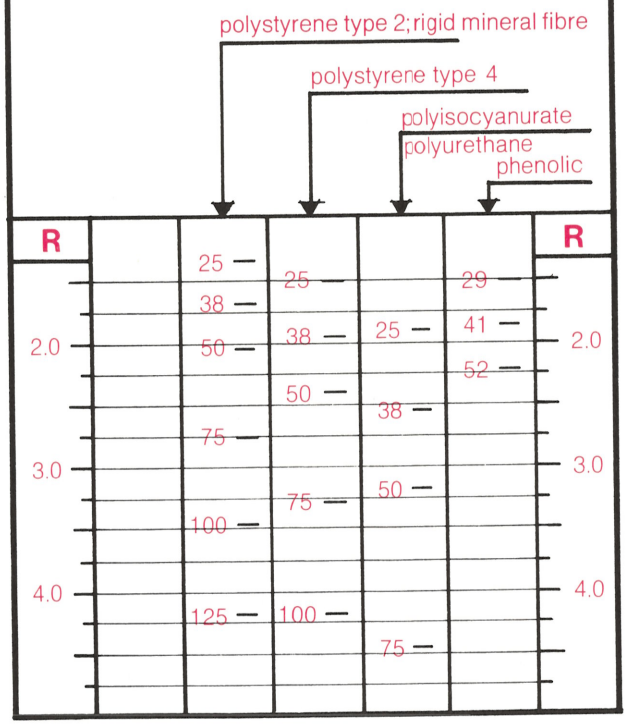
Table 4.6E Masonry Cavity and Veneer Walls

Precast/Block Wall Backup/Interior Insulation

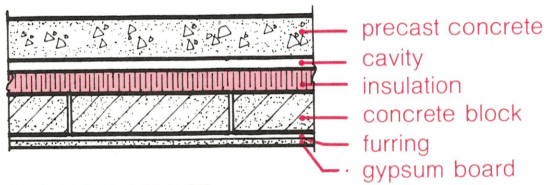


Uninsulated R-0.70

Insulation Type & Thickness mm.

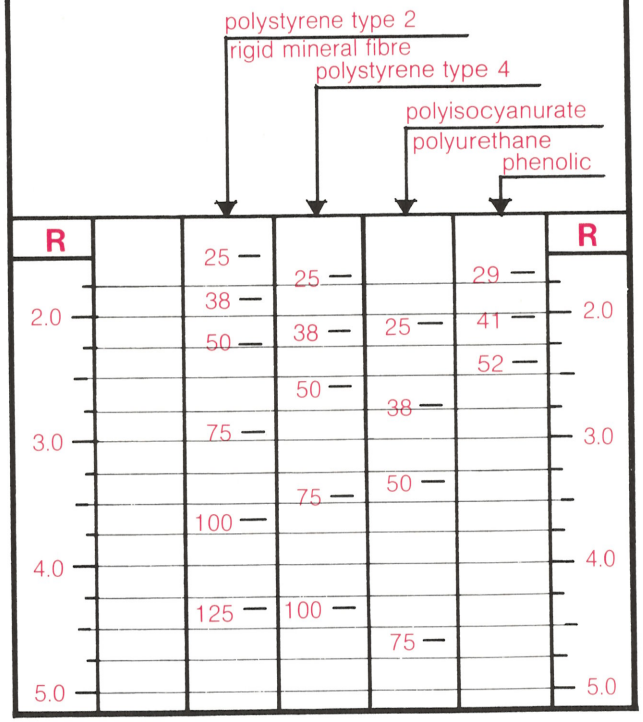


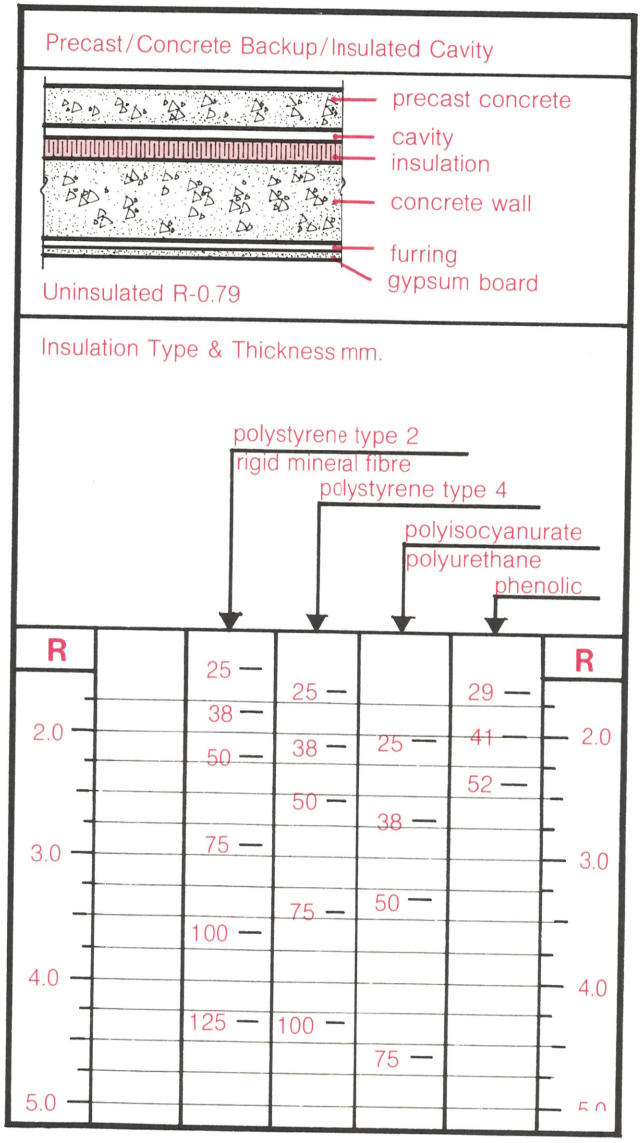
Precast/Block Backup Wall/Insulated Cavity



Uninsulated R-0.87

Insulation Type & Thickness mm.





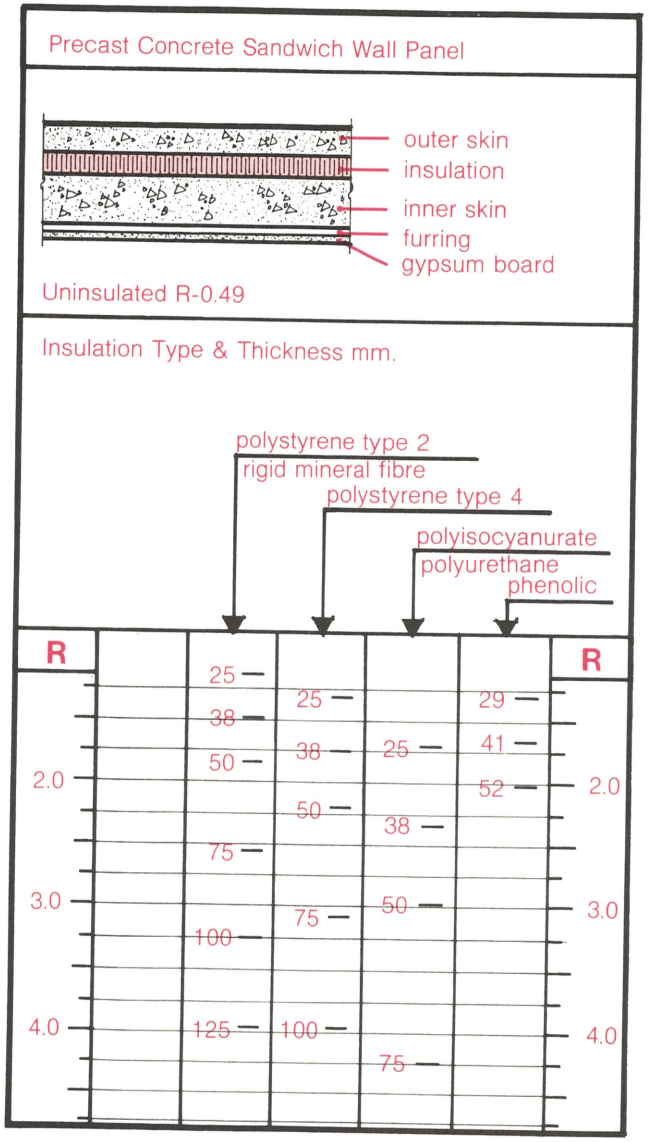
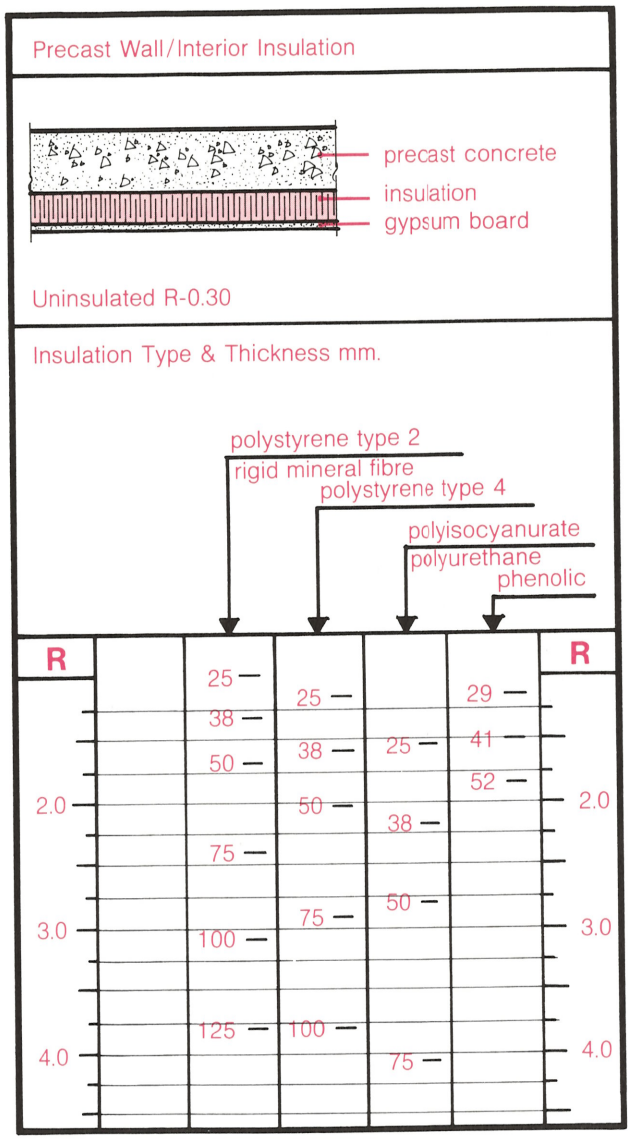


Table 4.6F Precast Concrete Walls



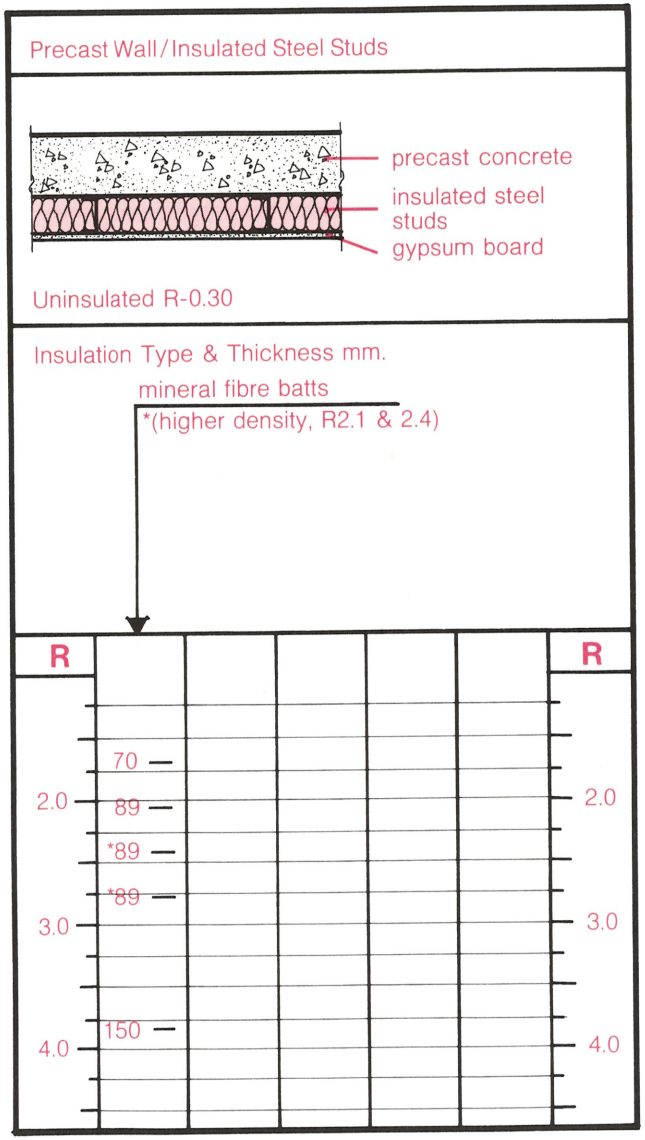
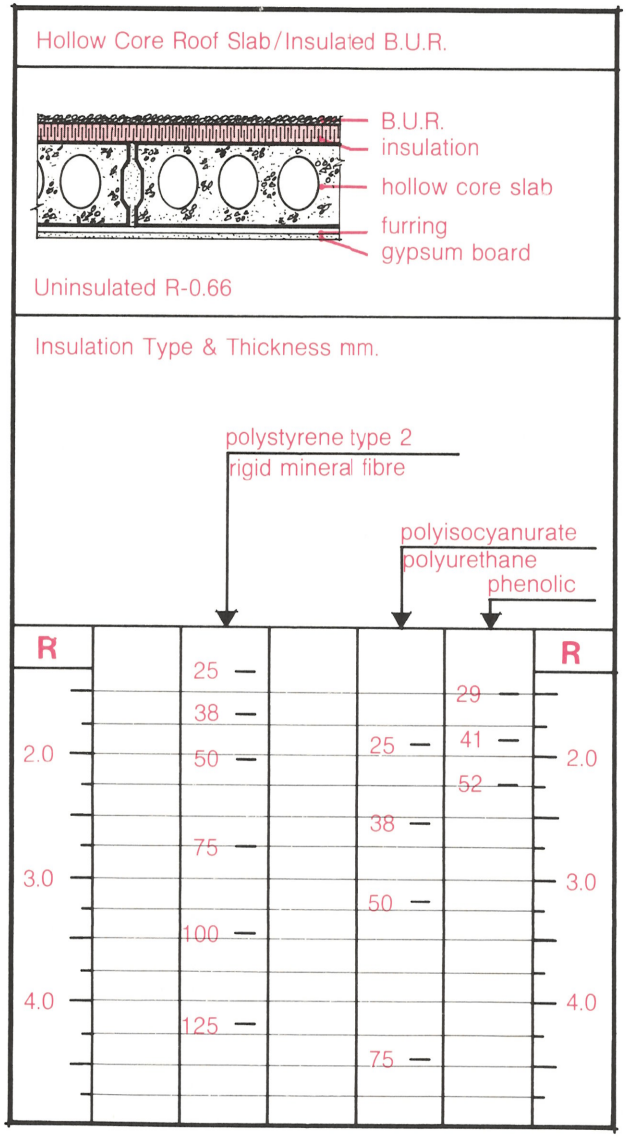


Table 4.6F Precast Concrete Walls (continued)



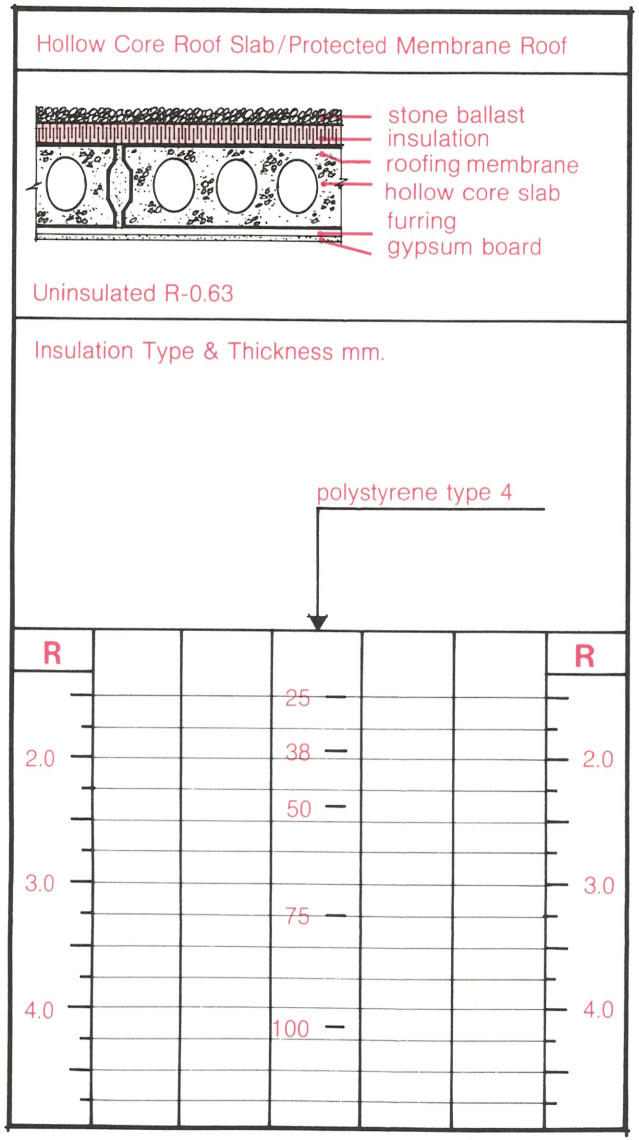
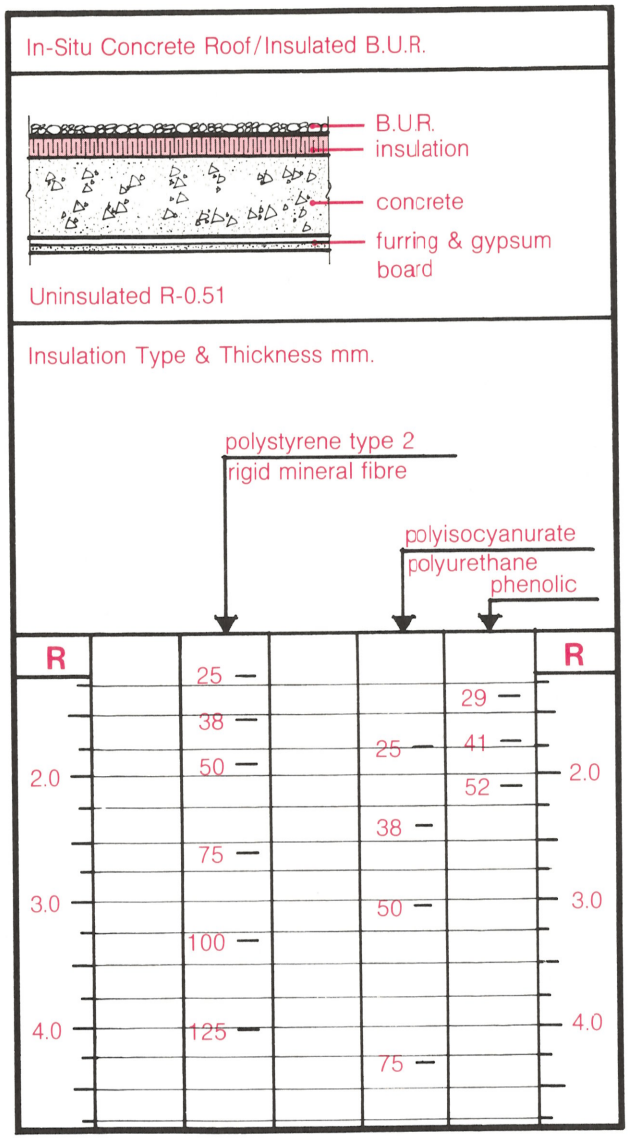


Table 4.6G Hollow-Core Slab Roofs



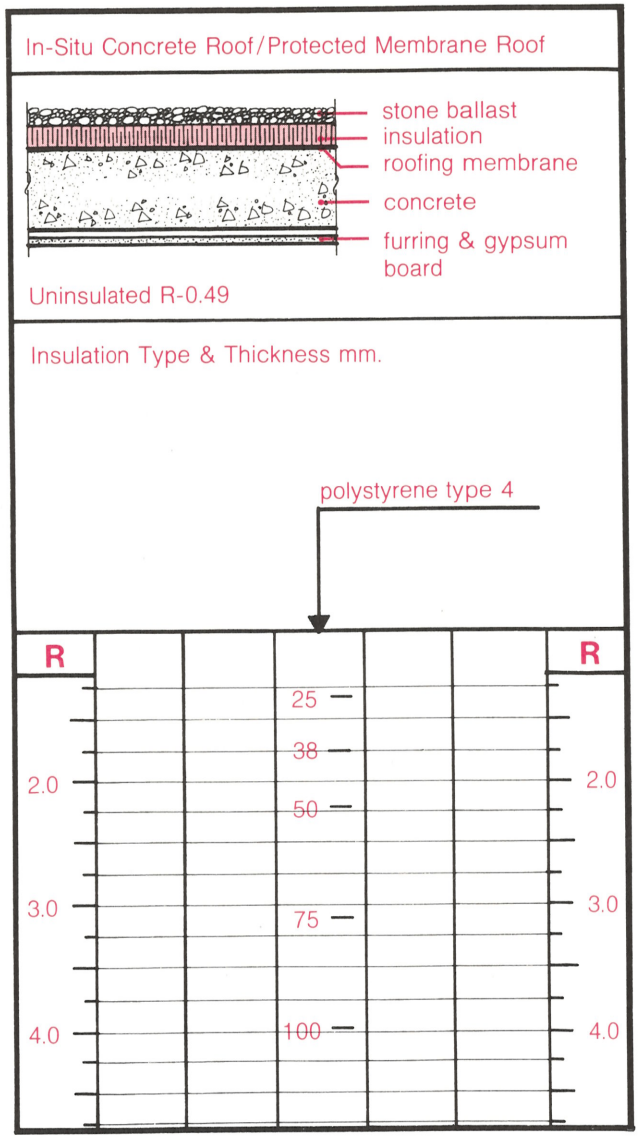
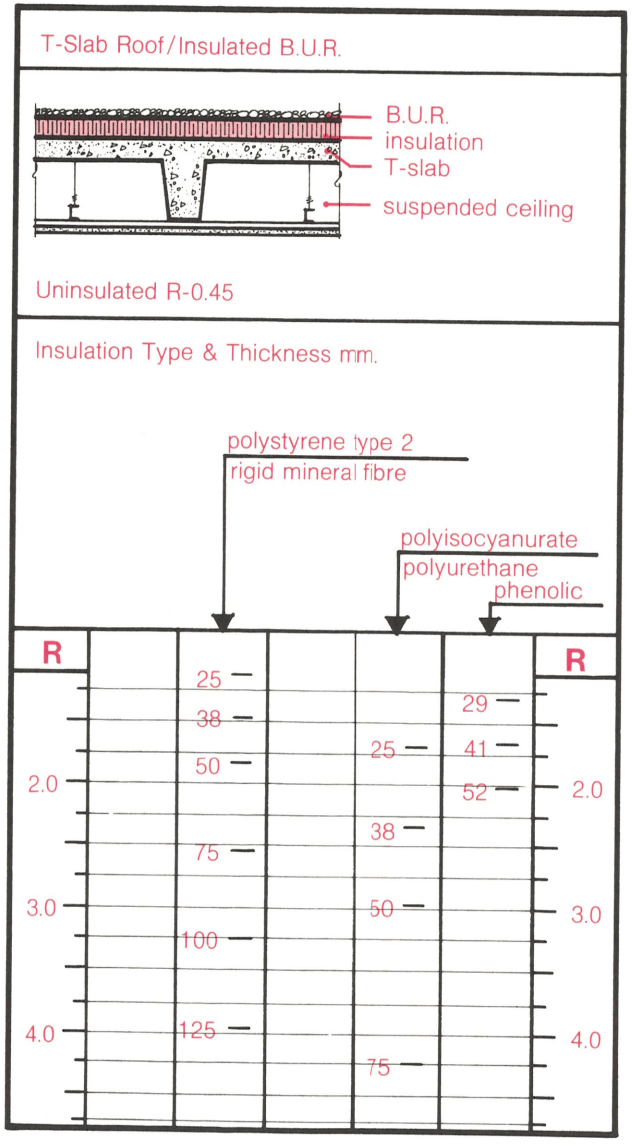


Table 4.6H In-Situ Concrete Roofs



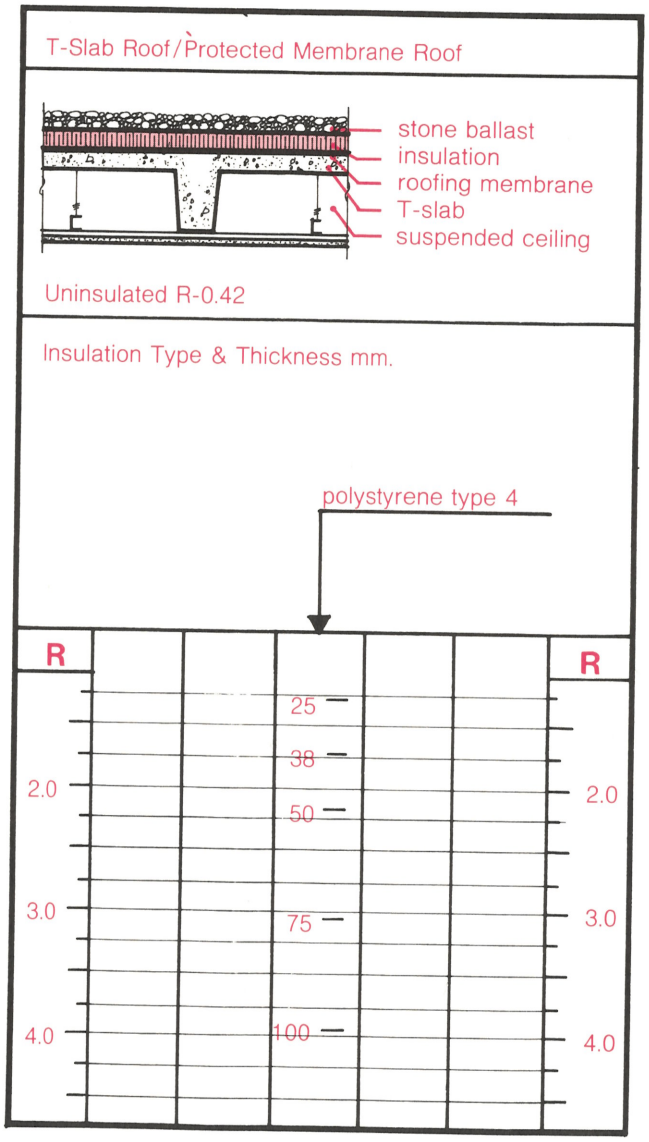


Table 4.6I T-Slab Roofs

4.7 References

1. Exterior Wall Construction in High Rise Buildings, NHA 5450
   — W.G. Plewes, P.Eng. for Canada Mortgage and Housing Corporation
   1981

2. Concrete Block Metric Technical Manual
   — Ontario Concrete Block Association

3. Rain Penetration and Masonry Wall Systems
   — J.I. Davison
   Building Practice Note No. 12
   Division of Building Research
   National Research Council of Canada
   1979

4. Rain Penetration and Design Detail for Masonry Walls
   — J.I. Davison
   Building Practice Note No. 13
   Division of Building Research
   National Research Council of Canada
   1979

5. Workmanship and Rain Penetration of Masonry Walls
   — J.I. Davison
   Building Practice Note No. 16
   Division of Building Research
   National Research Council of Canada
   1980

6. Concrete Masonry Handbook
   — Portland Cement Association

7. Construction Details and Their Effect on Building Behaviour
   — H. Morstead
   Alberta Masonry Institute

8. Recommended Details and General Information to Overcome Water Penetration and Vapour Movement in Exterior Masonry Wall Systems
   — Water Penetration Study Committee
   Borough of Scarborough

9. Brick Veneer High Rise Construction Technical Note 28B
   — Brick Institute of America
   1980

10. Manual for Structural Design of Architectural Precast Concrete
    — Prestressed Concrete Institute

11. National Building Code of Canada, 1980
    — Associate Committee on the National Building Code, National Research Council of Canada

12. CSA Standard A371-M1980
    Masonry Construction for Buildings
    — Canadian Standards Association

13. CSA Standard CAN 3-S304-M78
    Masonry Design and Construction for Buildings
    — Canadian Standards Association

14. CSA Standard A370
    Masonry Connectors
    — Canadian Standards Association
    (not yet published)

SECTION 5
CALCULATING ENERGY SAVINGS

In Section 2 it was suggested that the choice of economic thermal resistance values for all the components of a building's envelope should be part of the normal design process. In order for this to take place, the designer must be able to estimate the savings that will result from various levels of thermal resistance. This Section provides methods of doing so.

5.1 Buildings With Low "Free" Heat

In Subsection 2.2.1 the following equation for the annual conductive heat loss through a building envelope component was derived:

$$H_c = \frac{24\ A \cdot D}{R} \qquad (2.2.4)$$

where H_c is the annual heat loss due to conduction (W-hr),
A is the area of the component (m^2),
D is the degree-day accumulation over the heating season for the area where the building is located (°C-day), and
R is the thermal resistance of the component ($m^2 \cdot °C/W$)

In Subsection 2.3.1 the following equation for the rate of sensible heat loss due to air change was derived:

$$q_s = 0.335\ n \cdot v \cdot \Delta T \qquad (2.3.1)$$

where q_s is the rate of loss of sensible heat due to air exchange (W),
n is the number of exchanges of the complete volume of air in the building per hour,
v is the volume of the building (m^3), and
ΔT is the difference in temperature from inside to outside (°C)

It can readily be seen that, in a manner similar to that by which Equation 2.2.4 was derived, it is possible to derive from Equation 2.3.1 the following equation for the annual loss of sensible heat due to air change:

$$H_a = 24 \times 0.335\ \bar{n} \cdot v \cdot D \qquad (5.1.1)$$

where H_a is the annual loss of sensible heat from the building due to air change (W-hr), and
$\bar{n}$ is the average rate of air change over the heating season (air changes per hour)

Combining Equations 2.2.4 and 5.1.1, the total annual heat loss from the building can be expressed:

$$H_t = 24D \left(\lesssim \frac{A}{R} + 0.335\ \bar{n} \cdot v \right)^* \qquad (5.1.2)$$

where H_t is the total annual heat loss (W-hr) and $\lesssim \frac{A}{R}$ is the sum of $\frac{A}{R}$ for all components of the building envelope

It is common to make the following substitution:

$$G = \lesssim \frac{A}{R} + 0.335\ \bar{n} \cdot v \qquad (5.1.3)$$

where G is called the heat loss coefficient of the building (W/°C)

$$\therefore H_t = 24\ D \cdot G \qquad (5.1.4)$$

However, as was pointed out in Subsection 2.2.1, not all of this heat loss is purchased heat. Some of it is "free" heat from solar gains, from appliances, lighting and equipment and from the activities of the occupants. Taking this into account and also taking into account the fact that, in order to replace the energy lost through the building shell, the building's heating system must consume extra energy if its efficiency is less than 100%, the annual purchased energy can be expressed:

$$H_p = \frac{24\ D \cdot G - F}{E} \qquad (5.1.5)$$

where H_p is the amount of energy purchased annually specifically for space heating (W-hr),
F is the annual accumulation of free heat (W-hr), and
E is the heating system efficiency (%)

Figure 5.1A is a somewhat idealized graphical representation of the relationship between free and purchased heat. It is apparent in Figure 5.1 that there is a "hierarchy" of heat sources. For a given building and occupancy the free heat is more or less fixed and will be available whether needed for space heating purposes or not. Thus the free heat is the first source that will be used to make up the building's heat loss. Only when the heat loss exceeds the available free heat will the temperature tend to drop below the thermostat setting thus triggering the consumption of purchased energy by initiating the operation of the

*Equation 5.1.2 neglects the latent heat loss due to air change, also discussed in Subsection 2.3.1. This is a secondary effect which does not lend itself to annual analysis except by computer using detailed weather data.

heating system. Conversely, if the building shell is somehow improved to reduce heat loss, the purchased energy is the first to be saved, as shown in Figure 5.1B. However, as also shown in Figure 5.1B, upgrading the building shell also reduces the **useful** free heat since the free heat exceeds the heat loss more of the time. A recent study (1) of the relationship among H_t, F and G in houses could be interpreted as shown in Figure 5.2. This would result in the following equation:

$$H_p = \frac{20\ D \cdot G - F_f}{E} \qquad (5.1.6)$$

where F_f is the y-intercept of the free heat line in Figure 5.2

Using the subscripts "o" and "u" to designate "original" and "upgraded", Equation 5.1.6 can be used to calculate the saving due to a reduction in G as follows:

$$S = H_{po} - H_{pu}$$

$$= \frac{20\ D \cdot G_o - F_f}{E} - \frac{20\ D \cdot G_u - F_f}{E}$$

$$= \frac{20D}{E}(G_o - G_u) \qquad (5.1.7)$$

where S is the saving due to the reduced G value (W-hr)

Note that F_f drops out of the calculation. This means that savings can be calculated with more confidence than can actual annual energy consumption since the value of F_f is likely to vary from building to building. It should also be noted that the slope of the free heat line in Figure 5.2, 4 $\frac{\text{W-hr}}{\text{W/°C}}$, is based on certain assumptions about the heat generating activities in a house. This slope may not be appropriate for other types of occupancy which may produce more or less available free heat or even for houses which do not fit the assumptions made in Reference 1. (The most likely area where a significant difference would occur in houses would be in the amount of south-facing window and thus the amount of solar gains). Thus the factor 20 in Equations 5.1.6 and 5.1.7 should be applied with some caution to buildings other than ordinary houses. Unfortunately no similar data on other types of buildings was available at time of publication.

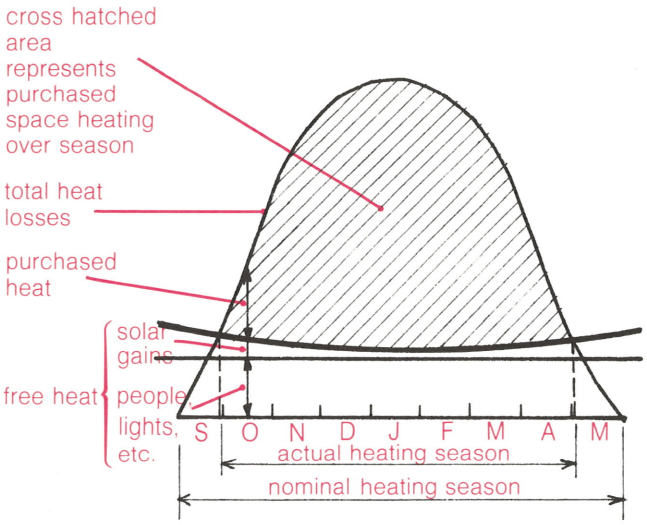


Figure 5.1A Relationship Between Free and Purchased Heat

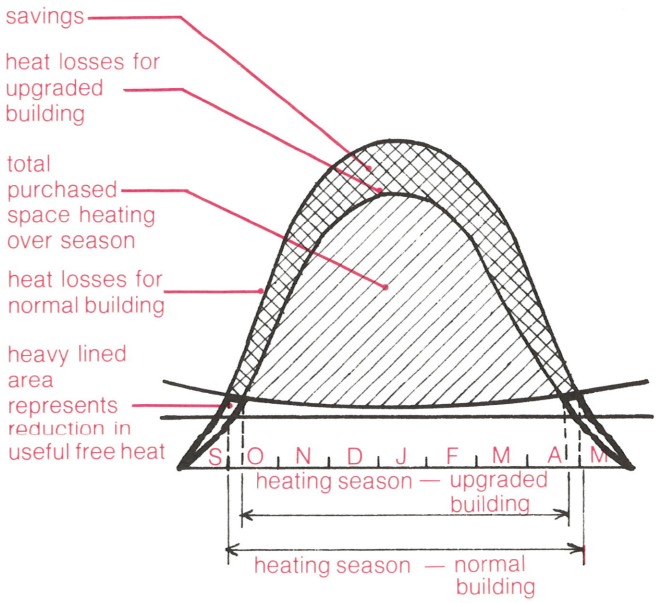

savings
heat losses for upgraded building
total purchased space heating over season
heat losses for normal building
heavy lined area represents reduction in useful free heat
S O N D J F M A M
heating season — upgraded building
heating season — normal building

Figure 5.1B Relationship Between Free and Purchased Heat for an Upgraded Building

With the above proviso, it is possible to proceed by recalling that

$$G = \sum \frac{A}{R} + 0.335\,\bar{n} \cdot v$$

Thus, if only one component of the envelope is upgraded by increasing its R value, and this upgrading does not alter the air change rate, the difference in G values will be —

$$G_o - G_{1u} = A_1 \left(\frac{1}{R_{1u}} - \frac{1}{R_{1o}} \right) \qquad (5.1.8)$$

and

$$S_1 = \frac{20D}{E} \cdot A_1 \cdot \left(\frac{1}{R_{1o}} - \frac{1}{R_{1u}} \right) \qquad (5.1.9)^*$$

where G_{1u} is the heat loss coefficient of the building after upgrading component 1 (W/°C),
A_1 is the area of component 1,
R_{1o} is the original R value of component 1 ($m^2 \cdot °C/W$),
R_{1u} is the upgraded R value of component 1 ($m^2 \cdot °C/W$), and
S_1 is the saving due to upgrading component 1 (W-hr)

Equation 5.1.9 may therefore be used for calculating energy savings due to increases in thermal resistance of individual building envelope components in buildings with low free heat. Such buildings include the following:

— ordinary houses with normal amounts of south-facing windows (i.e. not passive solar houses)
— motels
— heated warehouses

Example
What saving will result from increasing the R value of a 2500 m^2 motel roof in Regina from R2.5 to R3.5? The building is heated with a gas boiler, whose seasonal efficiency is estimated at 60%.

Degree days for Regina (from Appendix A) — 5921

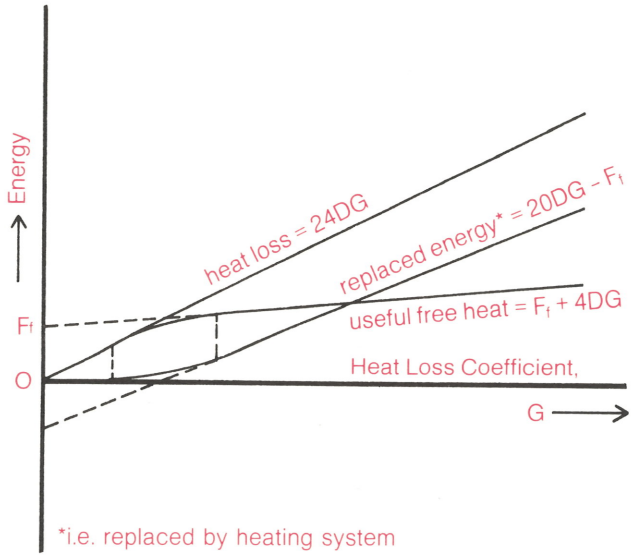


Figure 5.2 Relationship among Heat Loss, Free Heat and Heat Loss Coefficient in Houses.

*Note:
It is possible to derive a similar expression for savings due to improvements in airtightness. However, as there is no practical method for determining or estimating the value of $\bar{n}$ either before or after upgrading, this expression would have limited practical value.

From Equation 5.1.9

$$\text{Annual Saving} = \frac{20 \times 5921}{0.60} \times 2500 \times \left(\frac{1}{2.5} - \frac{1}{3.5}\right)$$

$$= 56.4 \times 10^6 \text{ W-hr}$$

$$= 56\,400 \text{ kWh}$$

To convert this to gigajoules, the more usual unit of energy where natural gas is involved, this figure is multiplied by 0.0036

$$\text{Annual Saving} = 56\,400 \times 0.0036$$
$$= 203 \text{ GJ}$$

Assume the cost of natural gas in Regina is \$0.08/m^3. From Table A.2, Appendix A, this is equivalent to \$2.16/GJ.

Therefore the reduction in heating cost in the first year due to upgrading the roof is —

$$203 \times 2.16 = \$438$$

This dollar saving will increase in future years as the price of natural gas increases.

5.2 Buildings With High "Free" Heat

Figure 5.3 is similar to Figure 5.1B but it has been re-drawn to indicate a building in which the free heat represents a much higher proportion of the total heat loss. In this case the reduction in useful free heat due to a small improvement in the building envelope is much more significant. Thus the slope of the free heat line in Figure 5.2 would be much higher and the factor in Equation 5.1.9 would be much lower than 20.

Another consideration is that Figure 5.3 may not be a very good representation of the relationship between free and purchased heat for some types of buildings. In a large office building, for example, even in the heart of the heating season the free heat may exceed the heat loss for some part of the day.

In either of the situations described above some significant part of the reduction in heat loss resulting from an improvement in the building envelope will be free heat. Thus the saving in purchased heat for space heating will be less for a given improvement than it would be in a building with low free heat.

Estimating savings in this type of building can only be done accurately by using fairly sophisticated computer modelling techniques. However the method described below can be used as a **very crude approximation**.

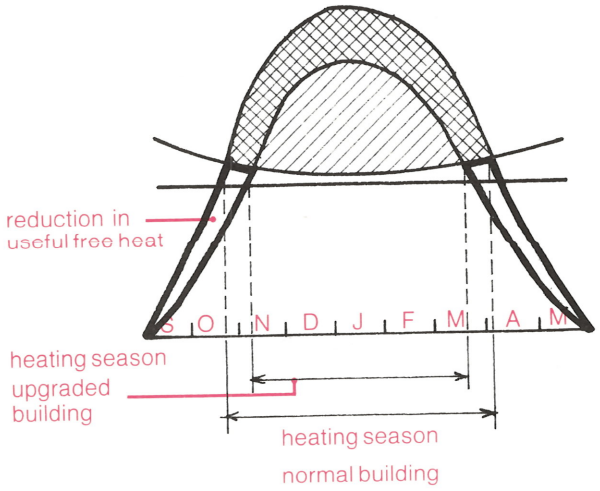


Figure 5.3 Significant Reduction in Useful Free Heat in an Upgraded Building with High Free Heat.

"Measures for Energy Conservation in New Buildings, 1978" is a model code issued by the Associate Committee on the National Building Code. Among other requirements, it prescribes minimum R values for building assemblies. These values were derived using a life cycle costing analysis (see Section 6) part of which involved annual heating calculations using a degree-day technique similar to that described in Subsection 5.1. In dealing with high free heat buildings the problems described above were encountered. It was decided to approximate the effect of high free heat by a reduction in the degree days. "Measures for Energy Conservation in New Buildings, 1978" defines high free heat buildings as those in which the total load of all wired-in interior lighting plus the total rated power of all fans and water pumps exceeds an average of 25 W/m^2 of floor area. For such buildings, the degree day values were, in effect, reduced by 1500. This suggests that for estimating savings due to upgrading R values in such buildings, Equation 5.1.9 should be modified as follows:

$$S_1 = \frac{20(D-1500)}{E} \cdot A_1 \cdot \left(\frac{1}{R_{1o}} - \frac{1}{R_{1u}}\right) \qquad (5.2.1)$$

Buildings likely to fall into this category include:

— passive solar houses
— large office buildings
— manufacturing buildings
— large retail buildings
— educational buildings

The proviso given in Subsection 5.1 regarding the applicability of the factor 20 in Equation 5.1.9 to buildings other than ordinary houses would also apply to Equation 5.2.1.

Example
A large office building in Toronto has 8000 m^2 of insulated wall. What saving will result from increasing the R value of the wall from R 1.7 to R 2.0? The building is heated with a well maintained gas boiler whose seasonal efficiency is estimated at 70%.

Degree days for Toronto (from Appendix A) — 4082

From Equation 5.2.1,
Annual Saving

$$= \frac{20(4082 - 1500)}{0.70} \times 8000 \times \left(\frac{1}{1.7} - \frac{1}{2.0}\right)$$

$= 52.1 \times 10^6$ W-hr

= 52 100 kWh

= 188 GJ

Assume the cost of natural gas in Toronto is \$0.14/m^3. From Table A.2, Appendix A, this is equivalent to \$3.78/GJ.

Therefore the reduction in heating cost in the first year due to upgrading the wall is —

$$188 \times 3.78 = \$711$$

5.3 Summary and Comments

For buildings with low free heat, calculate annual savings due to upgrading a component using —

$$S_1 = \frac{20D}{E} \cdot A_1 \cdot \left(\frac{1}{R_{1o}} - \frac{1}{R_{1u}}\right) \qquad (5.1.9)$$

For buildings with high free heat, calculate annual savings due to upgrading a component using —

$$S_1 = \frac{20(D - 1500)}{E} \cdot A_1 \cdot \left(\frac{1}{R_{1o}} - \frac{1}{R_{1u}}\right) \qquad (5.2.1)$$

It is obvious that the development of the above equations has involved a number of simplifying assumptions, some of which are very crude. Perhaps the crudest is the suggestion that all buildings can be grouped into just two free heat categories. Therefore judgement should be exercised in using these expressions. For example portions of a large office building may be thermally isolated from the high free heat sources (e.g. north-facing storage area) in which case Equation 5.1.9 might be more relevant in calculating the savings resulting from improvements to the exterior envelope in that area. Similarly, if a high free heat building also has a high amount of well-coupled mass to store the excess free heat, Equation 5.1.9 might be used to establish an upper limit of savings. Also, if a building is judged to be intermediate in terms of free heat, some value less than 1500 might be subtracted from the degree days. In some cases both Equations 5.1.9 and 5.2.1 could be used for the same envelope improvement to establish upper and lower bounds for the saving.

Another shortcoming of the methods presented in this section is that they do not address savings in cooling energy. Annual cooling energy calculations do not lend themselves to simple hand methods and can only be done by computer analysis. It is best to bear in mind, therefore, when using these methods to calculate savings in heating energy due to increased thermal resistance of the building envelope, that such increases are likely also to produce additional savings in cooling energy in cooled buildings even though it might not be possible to quantify such savings.

5.4 References

1. Sensitivity of Residential Heating Energy to Envelope Thermal Conductance
   — M.R. Bassett
   Building Research Note No. 177
   Division of Building Research
   National Research Council of Canada,
   October 1981

SECTION 6
COST-BENEFIT ANALYSIS

This Section presents methods of evaluating the cost of building envelope improvements relative to the savings in energy cost which each is expected to achieve.

Section 5 presented methods for estimating energy savings. It is beyond the scope of this Guide to deal with techniques for estimating building costs. It is assumed that this is a field in which building developers and designers are already well versed and in which the techniques are essentially the same for energy conserving buildings as for conventional buildings.

Once savings and costs are estimated, there are a number of methods available for weighing one against the other. All address, to some extent, the problem of comparing present costs with future savings.

When an owner builds a building and installs a heating or cooling system, he is effectively entering in an "open-ended" contract with his fuel supplier, in which the price of fuel needed for building operation can and often does increase at rates that are higher than the general inflation rate. The best protection against continual escalation of fuel costs for operation of a building is investment in energy conservation at the design stage of the building. Each successive fuel price increase then represents an increased return on investment (i.e. the amount of money saved by the investment continually increases).

On the other hand there is a cost of money involved to implement energy conservation measures: high interest rates increase the operating budget of a building. Also there is the opportunity cost to consider — what other investment opportunities must be foregone in order to invest in energy conservation. Trade-offs have to be made to arrive at the most favourable economic design.

A third factor must also be considered when investing in conservation measures — the principle of **diminishing returns** (less saving for the next dollar invested), which was discussed in Subsection 2.2.6.

The following methods, arranged in order of increasing complexity, will be presented:

- Simple payback period
- Annual cost
- Discounted payback period
- Rate of return
- Life cycle cost
- Optimum R value

The advantages and disadvantages of each method will be discussed and each will be illustrated by applying it to the following example:

Example Building:
Heated warehouse with 1000 m^2 of insulated wall
Location — Winnipeg — 5887 degree days
Heating — natural gas with 70% seasonal efficiency
Present fuel cost — \$0.11/m^3 = \$2.97/GJ

Three options are being considered:

Option	Wall R value ($m^2 \cdot °C/W$)	Initial Cost Increment	1st Year Saving
Base Case	2.8	0	0
1	4.3	\$1700	\$270
2	4.9	\$5100	\$350

A computer analysis of the base case building has estimated the annual cost of the heat lost through the walls at \$790. Other assumptions will be introduced as required for the various methods.

One "method" which will not be discussed in any detail, except to dismiss it here, is first cost comparison. First cost comparison is not normally a reliable indication of investment appeal or investment selection. What may appear to be a "bargain" with a low first cost may in fact be anything but a bargain, with a need for regular costly maintenance, energy waste, short life or other undesireable attributes. Alternatively, what may appear to be an expensive alternative, might in fact be a lower-cost, more reliable, and more desireable alternative when evaluated over a number of years of use.

6.1 Simple Payback Period

6.1.1 Method

In this simplest of all methods of evaluating energy conservation options the initial cost premium of an option is divided by the first year saving generated by the option to determine the number of years required for the saving to return the initial investment, assuming that energy costs (and hence the value of the energy saving) do not increase and that the investment carries no interest penalty.

6.1.2 Example

No further assumptions are needed.

Simple payback period for Option 1:

$$n_{sp} = \frac{1700}{270} = 6.3 \text{ years}$$

Simple payback period for Option 2:

$$n_{sp} = \frac{5100}{350} = 14.6 \text{ years}$$

Simple payback period for increment of Option 2 over Option 1:

$$n_{sp} = \frac{5100 - 1700}{350 - 270}$$

$$= 42.5 \text{ years}$$

6.1.3 Discussion

This method favours Option 1 over Option 2 but gives no indication whether either is a worthwhile investment relative to the base case.

The simplifying assumptions that energy costs will not go up and that the investment carries no interest penalty are obviously wrong but tend to offset one another. This method's main, and perhaps only, virtues are its simplicity and the fact that it does not require the designer to attempt to predict the future. It ignores the fact that the savings will continue to accrue beyond the payback period for the economic life of the building. This introduces the main difficulty with this method — the problem of defining what an acceptable payback period is. Certainly it should be less than the economic life of the building; but how much less? A person planning to own a building for only a short period of time and then sell it might be inclined to consider only those energy conservation options which yield payback periods less than the planned period of ownership. However this might not be a correct stance since, with increasing awareness of the cost of energy, failure to include other options could affect the building's resale value.

6.2 Annual Cost

6.2.1 Method

This method is most often used in the not-uncommon case where the initial investment in the building and any energy conserving features is paid not from the owner's own capital but with money borrowed in the form of a mortgage loan or other similar instrument. The method consists of a simple comparison, for the various options being considered, of the algebraic sums of the increases in financing charges and the energy costs.

6.2.2 Example

It is necessary to know the interest rate which will be charged on the borrowed money and the amortization period. Here the loan is assumed to be amortized over 20 years at a rate of 15% per annum.

	Base Case	Option 1	Option 2
Initial cost increment	0	$1700	$5100
Additional annual mortgage payment (1)	0	272	815
Annual heating cost (1st year)	$790	520	440
Total annual cost	$790	$ 792	$1255

(1) Mortgage payments are calculated using the equation:

$$A = P \cdot \frac{i}{[1-(1+i)^{-n}]} \qquad (6.2.1)$$

where A is the annual mortgage payment,
P is the principal (i.e. the amount of the loan),
i is the interest rate, and
n is the amortization period (years)

6.2.3 Discussion

This method also favours Option 1 over Option 2 and also indicates that Option 1 will have a marginally higher annual cost than the base case in the first year. However it gives no indication of how the relative worth of the three options will be affected by rising energy costs in future years.

The annual cost method is fairly simple and, like simple payback, does not require the designer to make any guesses about the future. However, it fails to provide a warning of possible cash flow problems in the future.

6.3 The Concept of Present Worth

Before going on to other cost-benefit analysis methods it is necessary to introduce the concept of "present worth" or "present value". This is best explained by example.

Suppose the cost of natural gas in Winnipeg increases at the rate of 12% per year. The annual cost of the heat loss through the walls of the warehouse of the example will increase according to the following schedule:

this year	+1	+2	+3	+4	...	+19	...
$790	885	991	1110	1243	...	6804	...

It is possible to calculate a sum of money which, if deposited in a bank or invested in an annuity and withdrawn according to the above schedule to pay these annual heating costs, would just be consumed (both principal and interest) at the end of the period under consideration. This amount is called the present worth of those annual heating costs. It is calculated using the following equations:

$$PW = \frac{C[1-(1+a)^{-n}]}{a} \qquad (6.3.1)$$

and

$$a = \frac{i-e}{1+e} \qquad (6.3.2)$$

where PW is the present worth of the heating costs over n years,
C is the annual heating cost in the first year,
a is the effective interest rate,
e is the rate at which energy costs are expected to increase,
i is the discount rate or cost of money, and
n is the number of years under consideration.

These last two factors require some further elaboration.

The discount rate can be a number of things. If the money were in fact deposited in a bank, it would be the interest rate offered by the bank. Another way to look at it would be to say the cost of money is the interest that would be paid on the best investment a building owner could make with the same amount of money if he did not invest in an energy conserving option.

The number of years to be considered is equally difficult to decide upon. It might be the amortization period of a mortgage. However, it can be argued that it should be the life of the building, which might be in excess of 100 years. It can also be argued that many building owners are unwilling to look beyond 10 years so this should be used. Perhaps it is reasonable to use the economic life of the building; i.e. that period over which the building is likely to remain useful without major renovations. This is probably in the area of 20 to 30 years for most types of buildings.

In the case of the Winnipeg warehouse, assuming it will have an economic life of 20 years and the owner could invest his money at 14% interest, the present worth of the heating costs would be calculated as follows:

$$a = \frac{0.14 - 0.12}{1.12} = 0.018$$

$$PW = \frac{790(1-1.018^{-20})}{0.018}$$

$$= 790 \times 16.7$$

$$= \$13\,170$$

The value 16.7 in the above calculation is called the "present worth factor" — the value by which the first year cost must be multiplied to determine present worth.

If the present worth factor is designated by F, its value is determined by

$$F = \frac{1-(1+a)^{-n}}{a} \qquad (6.3.3)$$

After doing several of these calculations, a designer will develop an appreciation of a reasonable range of values for the present worth factor and will be able to work directly with those values thereafter rather than going through the full calculations every time.

Present worth can be applied to energy savings as well as cost. In this case, C in Equation 6.3.1 is the first year saving and i in Equation 6.3.2 would be the interest rate on money borrowed to invest in the energy saving option. Thus the present worth of the savings achieved by Option 1 in the Winnipeg warehouse example would be calculated as follows:

$$a = \frac{0.15 - 0.12}{1.12} = 0.027$$

$$F = \frac{1 - 1.027^{-20}}{0.027} = 15.3$$

$$PW = 270 \times 15.3 = \$4131$$

The above discussion neglects the fact that heating costs may be tax deductible for some classes of building owners. Also investment income may be taxable. In these cases both the heating costs and interest rates used should be the "**after-tax**" values. If both fuel costs and investment income are affected by tax, the effects very nearly offset each other. The tax effects are very significant, however, for the common case of a private individual who cannot deduct fuel costs from taxable income, and who must pay income tax on income received from other revenue producing investments. When this type of

person weighs costs and benefits of an investment in an energy saving measure, he should calculate present worth using the after tax rate of interest he would obtain from the best investment open to him.

To illustrate, assume the owner of the Winnipeg warehouse could invest money at 14% but would pay income tax at a rate of 30% on the interest he received, the after tax rate of interest would be only 9.8% (0.7 × 14 = 9.8). Using this rate instead of 14% in the example case leads to a present worth of $19 629, which is $6459 more than when the effect of income tax is neglected. If, on the other hand, the heating cost is deductible from taxable income, the "after tax" heating cost is 30% lower than actual and the present worth would be $19 629 × 0.7 = $13 740.

For simplicity, tax considerations are not brought into the methods illustrated in subsequent subsections; but they should be kept in mind and taken into account where applicable.

6.4 Discounted Payback Period

6.4.1 Method

The discounted payback period is defined as that period of time over which the present value of the energy savings just equals the initial cost increment necessary to achieve the savings. Thus if the initial cost increment is substituted for PW and the first year saving for C in Equation 6.3.1, the equation can be solved for n to derive an expression for the discounted payback period.

$$n_{dp} = \frac{\ln(1-\frac{I}{S}\cdot a)}{\ln(\frac{1}{1+a})} \qquad (6.4.1)$$

where n_{dp} is the discounted payback period (years),
ln is the symbol for natural logarithm,
I is the initial investment, and
S is the first year saving

6.4.2 Example

The value of "a" as applied to savings in this example has already been established in Subsection 6.3 as 0.027

$$\text{for Option 1, } n_{dp} = \frac{\ln(1-\frac{1700}{270}\times 0.027)}{\ln(\frac{1}{1.027})}$$

$$= \frac{\ln\ 0.830}{\ln\ 0.974}$$

$$= 7.1 \text{ years}$$

and

$$\text{for Option 2, } n_{dp} = \frac{\ln(1-\frac{5100}{350}\times\ 0.027)}{\ln(\frac{1}{1.027})}$$

$$= \frac{\ln\ 0.607}{\ln\ 0.974}$$

$$= 19.0 \text{ years}$$

If one considers the incremental cost of Option 2 over Option 1

$$n_{dp} = \frac{\ln(1-\frac{3400}{80}\times 0.027)}{\ln(\frac{1}{1.027})}$$

$$= \frac{\ln(-0.1475)}{\ln\ 0.974}$$

Note that this last calculation involves the logarithm of a negative number and thus has no real answer. This means that, when the cost of money is taken into account, this last increment in investment will never be paid back.

6.4.3 Discussion

This method favours Option 1 over Option 2 but, like simple payback, gives no indication of their worth relative to the base case.

Although discounted payback takes into account the rising cost of energy and the cost of money, it shares all the other disadvantages of simple payback; namely that it ignores the savings beyond the payback period and that there is no self-evidently right value for payback period.

Also note that, because of the mutually-cancelling errors in the simplifying assumption associated with simple payback, there is not much difference between simple and discounted payback periods, at least when their values are in the range that most people would consider reasonable. Thus it is questionable whether the added effort required to calculate discounted payback is worthwhile.

6.5 Rate of Return

6.5.1 Method

The rate of return on an investment in energy conservation is the effective interest rate which would prevail if the present worth of the savings over the life of the investment just equalled the initial investment. To calculate this value the initial investment is substituted for PW and the first year saving for C in Equation 6.3.1, n is set equal to the economic life of the building and Equations 6.3.1 and 6.3.2 are solved for i. In actual practice it is easier to determine i by trial and error.

6.5.2 Example

Option 1

Try $i = 0.20$

$$a = \frac{0.20 - 0.12}{1.12} = 0.071$$

$$F = \frac{1 - 1.071^{-20}}{0.071} = 10.5$$

$$PW = 10.5 \times 270 = \$2838 > \$1700$$

Try $i = 0.30$

$$a = \frac{0.30 - 0.12}{1.12} = 0.161$$

$$F = \frac{1 - 1.161^{-20}}{0.161} = 5.9$$

$$PW = 5.9 \times 270 = \$1592 < \$1700$$

Try $i = 0.28$

$$a = \frac{0.28 - 0.12}{1.12} = 0.143$$

$$F = \frac{1 - 1.143^{-20}}{0.143} = 6.5$$

$$PW = 6.5 \times 270 = \$1757 \approx \$1700$$

Thus Option 1 provides a 28% rate of return over the economic life of the building.

In calculating the rate of return for Option 2 one should do so using the cost increment ($3400) and savings increment ($80) over Option 1. By a process similar to that illustrated above, this will be found to provide a rate of return of about 5%.

6.5.3 Discussion

This method indicates that Option 1, at least, may be a good investment relative to the base case but that going beyond Option 1 is not likely to be a good investment.

The advantage of this method over payback is that most building owners will have some predetermined notion of what rate of return they want to achieve on their investments and thus can readily compare the potential rate of return on a particular energy conservation option, not only with those on other energy conservation options, but also with the expected rates of return on all other available investment opportunities.

6.6 Life Cycle Cost

6.6.1 Method

The life cycle cost of an energy conservation option is the sum of the initial investment and the present worth of the heating costs associated with that option over its economic life. The lower the life cycle cost the more effective is the option.

6.6.2 Example

In Subsection 6.3, 15.3 was established as the present worth factor consistent with a 15% cost of money, a 12% rate of increase in the cost of energy and a 20 year economic life. This value is used in the following table:

	Base Case	Option 1	Option 2
1st Year Heating Cost	$790	$520	$440
Present Worth Factor	×15.3	×15.3	×15.3
Present Worth of Heating Costs	12 087	7956	6721
Initial Cost Increment	0	1700	5100
Life Cycle Cost	$12 087	$9656	$11 832

6.6.3 Discussion

This method indicates Option 1 is likely to be quite a good long term investment compared to the base case. Option 2, on the other hand, produces a life cycle cost which is only marginally lower than that of the base case and significantly higher than that of Option 1 and therefore this option should not be selected.

The life cycle cost method is a good way of taking account of all of the factors over the life of the building. However it can only be used to compare a number of options. There is no "target" life cycle cost figure against which to measure a single option.

6.7 Optimum R Value

6.7.1 Method

The fact that the life cycle cost of Option 1 was lower than those of either the base case or Option 2 suggests that there might be an optimum R value at which the life cycle cost is minimum. This is shown graphically in Figure 6.1. References 1 and 2 suggest an expression similar to the following for calculating optimum R value:

$$R_{opt} = \sqrt{\frac{20\,D \cdot B \cdot F}{M \cdot E}} \qquad (6.7.1)$$

where R_{opt} is the optimum R value ($m^2 \cdot °C/W$),
B is the present cost of energy ($/W-hr.), and
M is the cost per unit R per unit area ($/R·m²)

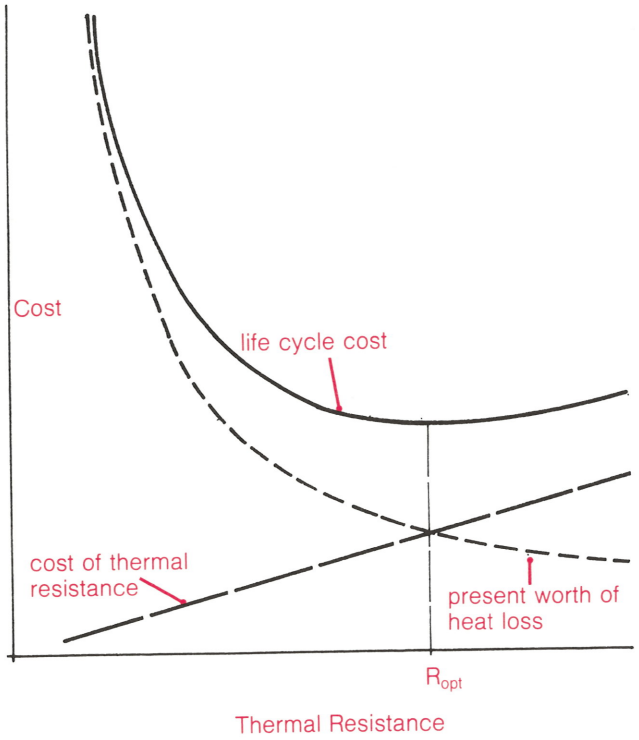


Figure 6.1 The Concept of Optimum R Value

6.7.2 Example

$$B = \$2.97/GJ$$

$$= 2.97 \times 3.6 \times 10^{-6}$$

$$= \$10.7 \times 10^{-6}/W\text{-hr.}$$

The use of Equation 6.7.1 is based on the assumption that there is a straight line relationship between R value and its cost as depicted in Figure 6.1. This is seldom exactly correct. For instance, in the warehouse example the cost per unit R averages $1.13/R·m² between the base case and Option 1, $5.67/R·m² between Option 1 and Option 2 and $2.43/R·m² between the base case and Option 2 (Figure 6.2). However, in view of the uncertainties involved in determining the other parameters in Equation 6.7.1, it is usually sufficiently accurate to use an average value determined by plotting the cost estimates for a large range of R values. Although insufficient points have been presented here to determine such an average, a separate study (3) has indicated that a reasonable value might be $1.68/R·m².

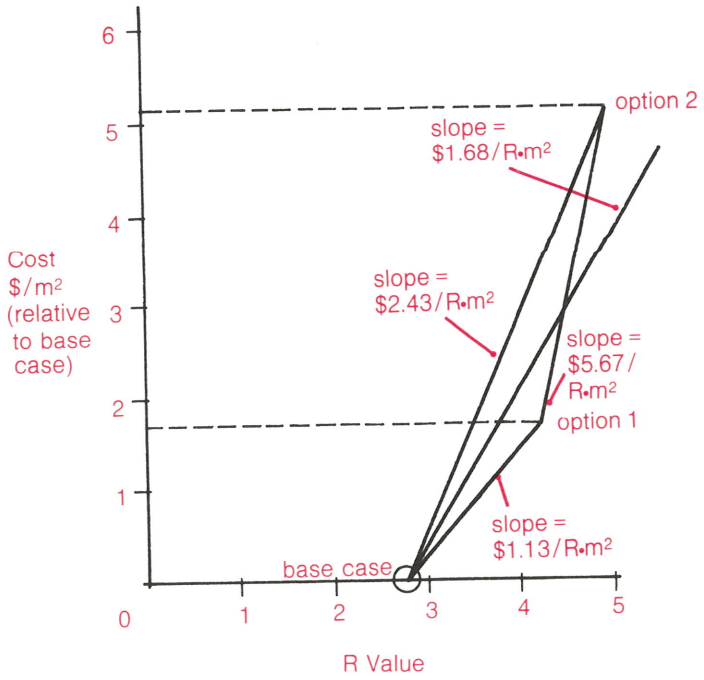


Figure 6.2 Unit Cost of R Value

$$M = \$1.68/R \cdot m^2$$

$$R_{opt} = \sqrt{\frac{20 \times 5887 \times 10.7 \times 10^{-6} \times 15.3}{1.68 \times 0.70}}$$

$$= 4.0\ m^2 \cdot °C/W$$

6.7.3 Discussion

Thus Option 1 is close to the optimum R, the base case is well below optimum and Option 2 is well beyond optimum (for this set of economic assumptions). In fact, Option 1 may be the optimum practical R value since the next lower available insulation thickness may take the R value well below the theoretical optimum.

The optimum R value method is a form of life cycle cost analysis which allows the designer to go directly to an optimum value once values for the economic parameters have been chosen and a relationship between construction cost and R value is known or can be assumed. It can, at least, be used to identify the range of R values where detailed analysis of individual options is worthwhile. The R value which produces the lowest life cycle cost is seldom as clearly delineated as is implied when a single value is derived from a formula. The life cycle cost curve in Figure 6.1 may be almost flat for several units either side of its lowest point, so that the life cycle cost for an R value slightly higher or lower than R_{opt} will be almost the same as that for R_{opt}. Most building developers or owners would therefore probably select an R value somewhat below R_{opt} rather than risk the added capital investment on the possibility of a marginal reduction in life cycle cost.

6.8 Summary

There is a wide variety of methods by which the benefits of an energy conserving option can be weighed against its cost. Each has its advantages and disadvantages. The method or methods which should be applied to a particular building will depend on the circumstances and the priorities of the building developer or owner. In the final analysis these methods only provide guidance and cannot replace the judgement of the building designer, developer and owner. Indeed this judgement is an essential ingredient even in the application of the cost-benefit analysis methods since most involve assumptions as to future conditions.

The following is a summary of the methods, formulae and symbols presented in this Section:

Simple Payback Period (6.1)

$$n_{sp} = \frac{I}{S}$$

Annual Cost (6.2)

$$\text{Annual Cost} = C + A$$

$$A = P \cdot \frac{i}{[1-(1+i)^{-n}]}$$

Present Worth (6.3)

$$PW = \frac{C[1-(1+a)^{-n}]}{a}$$

$$a = \frac{i-e}{1+e}$$

Present Worth Factor (6.3)

$$F = \frac{1-(1+a)^{-n}}{a}$$

Discounted Payback Period (6.4)

$$n_{dp} = \frac{\ln(1 - \frac{I}{S} \cdot a)}{\ln(\frac{1}{1+a})}$$

Rate of Return (6.5)

Solve for i in

$$I = \frac{S[1-(1+a)^{-n}]}{a}$$

$$a = \frac{i-e}{1+e}$$

Life Cycle Cost (6.6)

$$\text{Life cycle cost} = I + F \cdot C$$

Optimum R Value (6.7)

$$R_{opt} = \sqrt{\frac{20\,D \cdot B \cdot F}{M \cdot E}}$$

Symbols

A — annual mortgage payment ($)

a — effective interest rate (%)

B — present cost of energy ($/W-hr)

C — 1st year heating cost ($)

D — degree days (°C-days)

E — heating system efficiency (%)

e — rate of increase in energy costs (%)

F — present worth factor ($/$)

I — initial cost increment for energy conserving option ($)

i — discount rate or cost of money (interest rate) (%)

ln — natural logarithm

M — cost per unit of thermal resistance ($/R•m^2)

n — amortization period of mortgage or economic life of building (years)

n_{sp} — simple payback period (years)

n_{dp} — discounted payback period (years)

P — principal amount of mortgage loan ($)

PW — present worth of a future cost or saving ($)

R_{opt} — optimum R value (m^2•°C/W)

S — 1st year saving in heating cost due to an energy conserving option ($)

6.9 References

1. Determining the Optimum Thermal Resistance for Walls and Roofs
   — D.G. Stephenson
   Building Research Note No. 105
   Division of Building Research
   National Research Council of Canada
   January, 1976

2. Sensitivity of Residential Heating Energy to Envelope Thermal Conductance
   — M.R. Bassett
   Building Research Note No. 177
   Division of Building Research
   National Research Council of Canada
   October, 1981

3. The Cost of Insulating Various Types of Building Assembly
   — study for the National Research Council of Canada by
   Scanada Consultants Limited
   August, 1980

Appendix A: Design Data

Table A.1

Climatic Data For Selected Urban Areas(1)

Urban Area	Degree Days Below 18°C	Design Temperatures Jan 2½% °C	Design Temperatures July 2½% Dry °C	Hourly Wind Pressure 1/10, kN/m²(2)
Barrie	4613	-24	29	0.21
Belleville	4141	-22	29	0.32
Brandon	5965	-33	31	0.37
Brantford	3905	-17	30	0.31
Brockville	4206	-23	29	0.32
Calgary	5344	-31	29	0.40
Charlottetown	4623	-20	26	0.46
Chatham (Ont.)	3560	-16	31	0.32
Chicoutimi	5436	-30	28	0.25
Corner Brook	4778	-19	26	0.58
Cornwall	4419	-23	30	0.30
Dawson Creek	6152	-36	27	0.31
Drummondville	4678	-25	30	0.24
Edmonton	5590	-32	28	0.32
Flin Flon	6764	-38	27	0.42
Fredericton	4699	-24	29	0.30
Granby	4590	-25	29	0.26
Guelph	4262	-19	29	0.25
Halifax	4123	-16	26	0.40
Hamilton	3952	-17	31	0.36
Hull	4740	-25	30	0.30
Jonquiere	5650	-29	29	0.25
Kamloops	3755	-25	34	0.30
Kelowna	3647	-17	33	0.34
Kenora	5930	-33	28	0.20
Kingston	4176	-22	27	0.35
Kirkland Lake	6085	-33	30	0.29
Kitchener	4139	-19	29	0.27
London	4067	-18	30	0.36
Medicine Hat	4872	-31	33	0.39
Moncton	4707	-22	28	0.46
Montreal	4472	-23	30	0.31
Moose Jaw	5419	-32	32	0.36
Nanaimo	3304	- 7	26	0.47
Niagara Falls	3533	-16	30	0.33
North Battleford	6075	-34	30	0.45
North Bay	5318	-28	28	0.26
Oshawa	4130	-19	30	0.43
Ottawa	4674	-25	30	0.30
Owen Sound	4141	-19	29	0.33
Penticton	3513	-16	33	0.40
Peterborough	4395	-23	30	0.29
Port Alberni	3312	- 5	31	0.47
Portage la Prairie	5757	-31	30	0.36
Prince Albert	6563	-37	29	0.26
Prince George	5387	-33	28	0.25
Prince Rupert	4383	-14	19	0.42
Québec	5080	-25	28	0.38
Red Deer	5846	-32	29	0.31

Table A.1 (continued)

Climatic Data For Selected Urban Areas[1]

Urban Area	Degree Days Below 18°C	Design Temperatures Jan 2½% °C	Design Temperatures July 2½% Dry °C	Hourly Wind Pressure 1/10, kN/m²[2]
Regina	5921	-34	31	0.34
Rimouski	5226	-25	25	0.48
St. Catharines	3512	-16	30	0.36
St. Hyacinthe	4583	-24	30	0.27
St. Jean	4490	-24	29	0.31
Saint John	4771	-22	25	0.38
St. John's	4802	-14	24	0.60
St. Thomas	3916	-16	31	0.33
Sarnia	3899	-16	31	0.35
Saskatoon	6077	-35	30	0.36
Sault Ste. Marie	5089	-25	29	0.32
Sept-Iles	6136	-30	24	0.69
Shawinigan	5007	-26	29	0.19
Sherbrooke	4585	-28	29	0.21
Sorel	4741	-24	30	0.24
Stratford	4287	-18	29	0.33
Sudbury	5446	-28	29	0.29
Swift Current	5483	-32	32	0.46
Sydney	4459	-16	27	0.47
Thetford Mines	5221	-26	28	0.36
Thunder Bay	5744	-31	28	0.25
Timmins	6188	-34	30	0.25
Toronto	4082	-18	31	0.39
Trail	3639	-17	33	0.17
Trois Rivieres	4953	-25	29	0.22
Truro	4658	-21	27	0.37
Val d'Or	6146	-33	29	0.24
Vancouver	3005	- 7	26	0.45
Vernon	3838	-20	33	0.32
Victoria	3075	- 5	24	0.48
Welland	3673	-15	30	0.33
Windsor (Ont.)	3590	-16	31	0.29
Winnipeg	5887	-33	30	0.35

(1) Source: The Supplement to the National Building Code of Canada, 1980 (NRCC No. 17724).

(2) Hourly average pressure with 1 chance in 10 of being exceeded in any one year. This is the reference pressure used in cladding design under Part 4 of the National Building Code of Canada, 1980.

Energy Cost Equivalents

Table A.2

Gas Cost Equivalents

$/MCF	$/m³	$/GJ
1.00	0.0353	0.945
1.60	0.0565	1.51
1.70	0.0600	1.60
1.80	0.0635	1.70
1.90	0.0671	1.79
2.00	0.0706	1.89
2.10	0.0741	1.98
2.20	0.0777	2.08
2.30	0.0812	2.17
2.40	0.0847	2.26
2.50	0.0883	2.36
2.60	0.0918	2.45
2.70	0.0953	2.55
2.80	0.0988	2.64
2.90	0.1024	2.74
3.00	0.1060	2.83
3.10	0.1094	2.92
3.20	0.1130	3.02
3.30	0.1165	3.11
3.40	0.1200	3.21
3.50	0.1236	3.30
3.60	0.1271	3.40
3.70	0.1306	3.49
3.80	0.1341	3.58
3.90	0.1377	3.68
4.00	0.1412	3.77
4.25	0.1500	4.01
4.50	0.1589	4.25
4.75	0.1677	4.48
5.00	0.1765	4.72
5.25	0.1853	4.95
5.50	0.1942	5.19
5.75	0.2030	5.42
6.00	0.2118	5.66
6.25	0.2206	5.90
6.50	0.2295	6.13
6.75	0.2383	6.37
7.00	0.2471	6.60

Table A.3

Oil Cost Equivalents

$/gal.	$/L	$/GJ
0.70	0.154	4.00
0.72	0.158	4.12
0.74	0.163	4.23
0.76	0.167	4.35
0.78	0.172	4.46
0.80	0.176	4.58
0.82	0.180	4.69
0.84	0.185	4.80
0.86	0.189	4.92
0.88	0.194	5.03
0.90	0.198	5.15
0.92	0.202	5.26
0.94	0.207	5.38
0.96	0.211	5.49
0.98	0.216	5.60
1.00	0.220	5.72
1.02	0.224	5.83
1.04	0.229	5.95
1.06	0.233	6.06
1.08	0.238	6.18
1.10	0.242	6.29
1.12	0.246	6.41
1.14	0.251	6.52
1.16	0.255	6.63
1.18	0.260	6.75
1.20	0.264	6.86
1.25	0.275	7.15
1.30	0.286	7.43
1.35	0.297	7.72
1.40	0.308	8.01
1.45	0.319	8.29
1.50	0.330	8.58
1.55	0.341	8.86
1.60	0.352	9.15
1.65	0.363	9.44
1.75	0.385	9.72

Table A.4

Electricity Cost Equivalents

$/kWh	$/GJ
0.010	2.78
0.015	4.17
0.020	5.56
0.021	5.83
0.022	6.11
0.023	6.39
0.024	6.67
0.025	6.94
0.026	7.22
0.027	7.50
0.028	7.78
0.029	8.06
0.030	8.33
0.031	8.61
0.032	8.89
0.033	9.17
0.034	9.44
0.035	9.72
0.036	10.00
0.037	10.28
0.038	10.56
0.039	10.83
0.040	11.11
0.042	11.67
0.044	12.22
0.046	12.78
0.048	13.33
0.050	13.89
0.052	14.44
0.054	15.00
0.056	15.56
0.058	16.11
0.060	16.67
0.062	17.22
0.064	17.78
0.066	18.33
0.068	18.89
0.070	19.44

Table A.5

Thermal Resistance Values (R Values) For Various Construction Materials

Except where noted, the following values are taken from the Canada Mortgage and Housing Corporation publication "Energy Conservation in New Small Residential Buildings".

In this regard, materials can be separated into two principal categories as follows:

— Materials which are assessed on a generic basis such as wood, concrete or bricks. The values given for this category are the only values officially recognized by CMHC.

— Materials which are assessed on a product-by-product basis. Most insulation materials fall into this category. The values given for this category are indicated in **bold face** and are average values provided for guidance only. The values recognized by CMHC for specific products are given in CMHC's Acceptable Building Materials Systems and Equipment Manual (ABM) which is available for examination at CMHC offices.

All values are given in $m^2 \cdot °C/W$.

	Thermal Resistance	
Description	**Per mm**	**For Thickness Listed**
Air Surface Films		
Still Air-Horizontal Surface — Heat Flow Up — e.g. inside of ceilings		0.105
Still Air Horizontal Surface — Heat Flow Down — e.g. inside of floors		0.162
Still Air-Vertical Surface — Heat Flow Horizontal — e.g. inside of walls		0.120
Moving Air — Any Position — e.g. outside of any surface		0.030
Air Spaces — Faced with Non-reflective Materials — 12 mm Minimum Dimension		
Horizontal Space — Heat Flow Up		0.150
Horizontal Space — Heat Flow Down		0.180
Vertical Space — Heat Flow Horizontal		0.171
Air Spaces Less than 12 mm in Minimum Dimension		0

Table A.5 (continued)

Description	Thermal Resistance Per mm	Thermal Resistance For Thickness Listed
Air Spaces — Faced with Reflective Materials* — 12 mm Minimum Dimension		
Horizontal Space-Faced 1 Side — Heat Flow Up		0.324
Horizontal Space-Faced 2 Sides — Heat Flow Up		0.332
Horizontal Space-Faced 1 Side — Heat Flow Down		0.980
Horizontal Space-Faced 2 Sides — Heat Flow Down		1.034
Vertical Space-Faced 1 Side — Heat Flow Horizontal		0.465
Vertical Space-Faced 2 Sides — Heat Flow Horizontal		0.480
Air Spaces Less than 12 mm in Minimum Dimension		0
Insulation		
Mineral Wool and Glass Fibre	**0.0208**	
Cellulose Fibre	0.0253	
Vermiculite	**0.0144**	
Wood Fibre	**0.0231**	
Wood Shavings	**0.0169**	
Sprayed Asbestos	0.0201	
Expanded Polystyrene Complying with CGSB 51-GP-20M (1978)		
— TYPE 1	0.0257	
— TYPE 2	0.0277	
— TYPE 3	0.0298	
— TYPE 4	0.0347	
Rigid Glass Fibre Roof Insulation	**0.0277**	
Natural Cork	**0.0257**	
Rigid Urethane or Isocyanurate Board	0.0420	
Mineral Aggregate Board	**0.0182**	
Compressed Straw Board	**0.0139**	
Fibreboard	**0.0194**	
Phenolic Thermal Insulation	0.0304	
Structural Materials		
Cedar Logs and Lumber	0.0092	
Other Softwood Logs and Lumber	0.0087	
Concrete:		
— 2400 kg/m³	0.00045	
— 1760 kg/m³	0.0013	
— 480 kg/m³	0.0069	
(See also Figure A.1)		
Concrete Block — 3 Oval Core		
Sand and Gravel Aggregate		
— 100 mm		0.125
— 200 mm		0.195
— 300 mm		0.225

* These values may not be used in calculations for areas where the mean annual total degree days exceed 4400 Celsius degree days.

Table A.5 (continued)

Description	Thermal Resistance Per mm	Thermal Resistance For Thickness Listed
Structural Materials		
Cinder Aggregate		
— 100 mm		0.125
— 200 mm		0.195
— 300 mm		0.225
Lightweight Aggregate		
— 100 mm		0.264
— 200 mm		0.352
— 300 mm		0.400
Concrete Block — Rectangular Core, Metric Sizes*		
Normal Density (2100 kg/m³)		
— No Insulation in Cores		
— 90 mm		0.17
— 140 mm		0.19
— 190 mm		0.21
— 240 mm		0.24
— 290 mm		0.26
— Cores Filled with Vermiculite		
— 90 mm		—
— 140 mm		0.40
— 190 mm		0.51
— 240 mm		0.61
— 290 mm		0.69
Low Density (1700 kg/m³)		
— No Insulation in Cores		
— 90 mm		0.24
— 140 mm		0.26
— 190 mm		0.30
— 240 mm		0.33
— 290 mm		0.36
— Cores Filled with Vermiculite		
— 90 mm		—
— 140 mm		0.62
— 190 mm		0.81
— 240 mm		0.98
— 290 mm		1.13

* Values for rectangular core concrete block are taken from "Concrete Block Metric Technical Manual", Ontario Concrete Block Association, 1979.

Table A.5 (continued)

Description	Thermal Resistance Per mm	Thermal Resistance For Thickness Listed
Sheathing Materials		
Softwood Plywood	0.0087	
Mat-Formed Particle Board	0.0087	
Insulating Fibreboard Sheathing	**0.0165**	
Gypsum Sheathing	0.0062	
Sheathing Paper		0.011
Asphalt Coated Kraft Paper Vapour Barrier		Negligible
Polyethylene Vapour Barrier		Negligible
Cladding Materials		
Fibreboard Siding	0.0107	
Softwood Siding		
Drop — 18 × 184 mm		0.139
Bevel — 12 × 184 mm — Lapped		0.143
Bevel — 19 × 235 mm — Lapped		0.185
Plywood — 9 mm — Lapped		0.103
Brick		
Clay or Shale — 100 mm		0.074
Concrete and Sand/Lime — 100 mm		0.053
Stucco	0.0014	
Metal Siding		
Horizontal Clapboard Profile		0.123
Horizontal Clapboard Profile with Backing		0.246
Vertical V-Groove Profile		0.123
Vertical Board and Batten Profile		Negligible
Roofing Materials		
Asphalt Roll Roofing		0.026
Asphalt Shingles		0.078
Built-Up Roofing		0.058
Wood Shingles		0.165
Crushed Stone — Not Dried	0.0006	
Interior Finish Materials		
Gypsum Board, Gypsum Lath	0.0062	
Gypsum Plaster — Sand Aggregate	0.0014	
Gypsum Plaster — Lightweight Aggregate	0.0044	
Plywood	0.0087	
Hard-Pressed Fibreboard	0.0050	
Insulating Fibreboard	0.0165	
Mat-Formed Particleboard	0.0087	
Carpet Fibrous Underlay		0.366
Carpet Rubber Underlay		0.226
Resilient Floor Coverings		0.014
Terrazzo — 25 mm		0.014
Hardwood Flooring — 9.5 mm		0.060
— 19 mm		0.120
Wood Fibre Tiles — 13 mm		0.209

Table A.6

Vapour Resistance Values of Various Materials

Material	Thickness (mm)	Vapour Resistance (Pa•m²•s/ng)	Vapour Resistance per mm
Plastic and Metal Foils and Films			
Aluminum foil	0.025		
Aluminum foil	0.009	0.35	
Polyethylene	0.05	0.11	21 114.
Polyethylene	0.10	0.22	21 114.
Polyethylene	0.15	0.30	21 114.
Polyethylene	0.20	0.44	21 114.
Polyethylene	0.25	0.58	21 114.
Polyvinylchloride, unplasticized	0.05	0.026	
Polyvinylchloride, plasticized	0.10	0.013-0.023	
Polyester	0.025	0.025	
Polyester	0.008	0.075	
Polyester	0.02	0.22	
Cellulose acetate	0.25	0.0035	
Cellulose acetate	3.18	0.054	
Construction Materials			**(×10⁻⁴)**
Concrete (1:2:4 mix)			2.11
Brick masonry	102.0	0.023	
Concrete block (cored, limestone aggregate)	203.0	0.007	
Tile masonry, glazed	102.0	0.145	
Asbestos cement board	3.05	0.0018-0.0036	
With oil base finishes		0.035 -0.07	
Plaster on metal lath	19.0	0.0012	
Plaster on wood lath		0.0016	
Plaster on plain gypsum lath (with studs)		0.0009	
Gypsum wall board (plain)	9.5	0.00035	
Gypsum sheathing (asphalt impreg.)	12.7		0.341
Structural insulating board (sheathing qual.)			0.136-0.341
Structural insulating board (interior, uncoated)	12.7	0.00019-0.00035	
Hardboard (standard)	3.18	0.0016	
Hardboard (tempered)	3.18	0.0035	
Wood, sugar pine			1.29-17.03
Plywood (douglas fir, exterior glue)	6.35	0.025	
Plywood (douglas fir, interior glue)	6.35	0.009	
Acrylic, glass fiber reinforced sheet	1.42	0.145	
Polyester, glass fiber reinforced sheet	1.22	0.35	
Thermal Insulations			
Air (still)			0.057
Cellular glass			∞
Corkboard			2.59-3.27
Mineral wool (unprotected)			0.059
Expanded polyurethane (R-11 brown) board stock			4.22-17.03
Expanded polystyrene — extruded			5.65
Expanded polystyrene — bead			1.16-3.4
Phenolic foam (covering removed)			0.259
Unicellular synthetic flexible rubber foam			45.6-340.6

Table A.7

Conversion Factors

Multiply		By	To Convert To	
Unit	Abbrev.		Unit	Abbrev.
millimeter	mm	0.039 37	inch	in.
meter	m	39.37	inch	in.
meter	m	3.281	feet	ft.
square millimeter	m^2	0.001 550	square inch	$in.^2$
square meter	m^2	10.76	square feet	$ft.^2$
cubic meter	m^3	35.31	cubic feet	$ft.^3$
cubic meter	m^3	1000.0	litre	L
litre	L	0.2200	imperial gallon	gal.
cubic meter per second	m^3/s	2119.0	cubic feet per minute	cfm
litre per second	L/s	2.119	cubic feet per minute	cfm
gram	g	0.3527	ounce	oz.
kilogram	kg	2.205	pound	lb.
pascal	Pa	0.0040	inch water gauge	in. H_2O
pascal	Pa	0.000 145	pounds per square inch	psi
pascal	Pa	0.001	kilopascal	kPa
joule	J	10^{-6}	megajoule	MJ
joule	J	10^{-9}	gigajoule	GJ
megajoule	MJ	947.8	British Thermal Unit	BTU
kilowatt-hour	kWh	3.60	megajoule	MJ
kilowatt-hour	kWh	3413.0	British Thermal Unit	BTU

NOTE: To convert °C to °K add 273

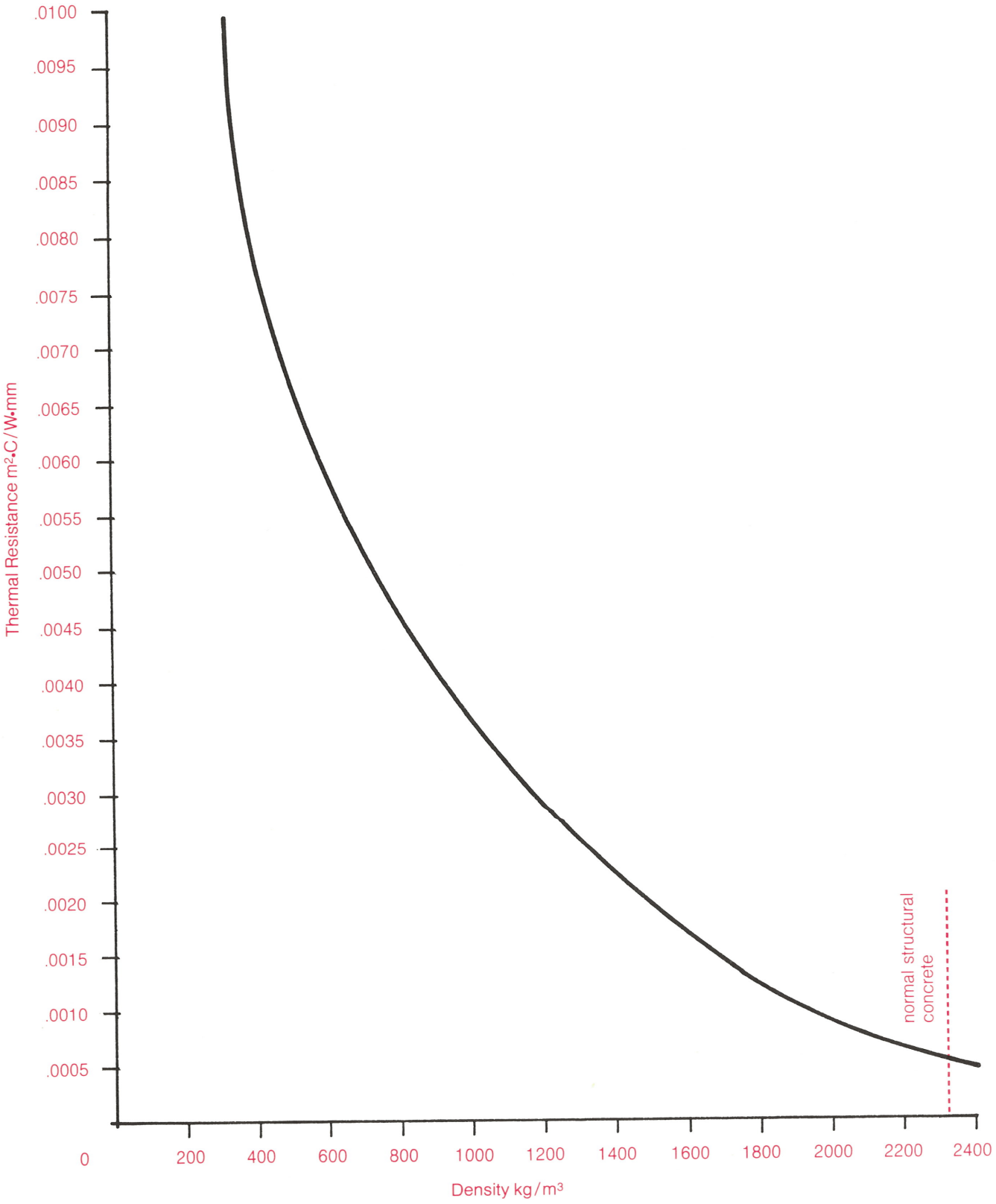


Figure A.1 Thermal Resistance of Concrete Versus Density
Source: Concrete Energy Conservation Guidelines, Portland Cement Association, 1980

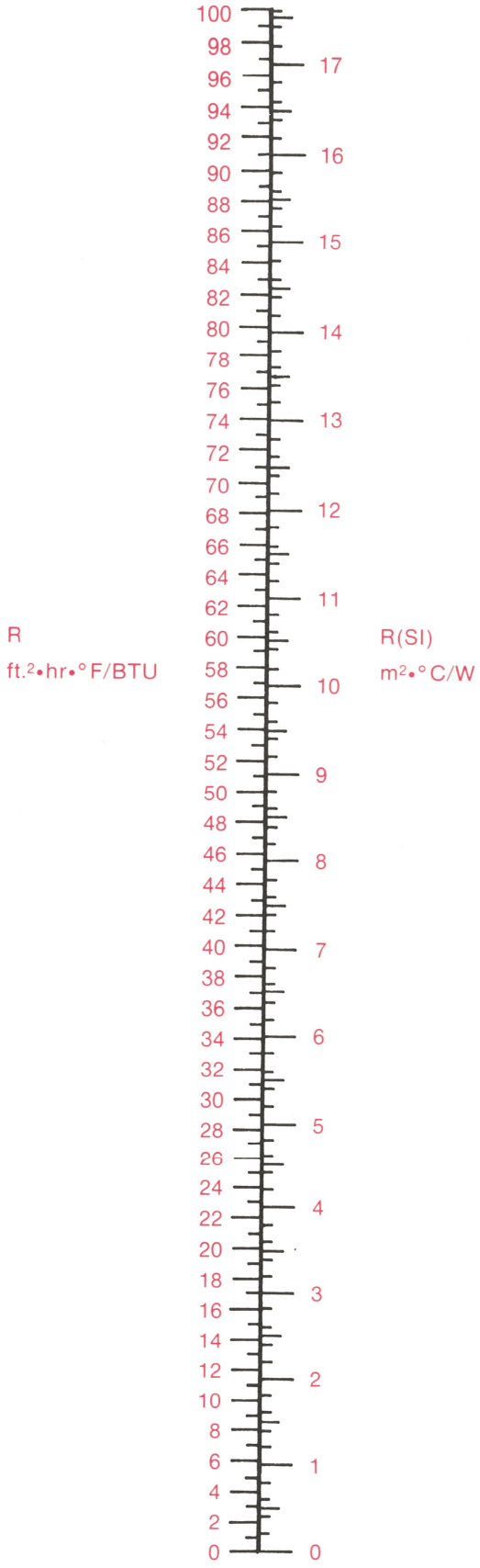


Figure A.2 R Value Conversion Scale

Appendix B: Quantifying the Benefits of Mass

In this appendix, modelling procedures and problems are discussed with respect to quantifying the benefits of mass, and the use of the mass effect allowance specified in code requirements is explained and illustrated.

B.1 The Detailed Analytical Model Approach

The quantification of annual heat energy saving due to the additional mass in heavy construction of a building can only be done reliably by detailed energy modelling of a building for a full heating season.

To date, no sophisticated program is available that properly models the dynamic energy flows inside a building where mass is "doing its work". In these models, factors that are believed to be important (e.g. thermal coupling between mass, heat sources and heat loss areas) are usually estimated for the purpose of first approximations of the mass effect.

Perhaps the largest single error in these approximations is that all or large portions of interior mass is assigned an average thermal coupling. As discussed in the main text some portion of the structural mass is well coupled, other portions are not, depending on location, surface finish, air circulation, etc. The assumption of average coupling may overestimate the amount of mass that actually takes part in energy storage. This has the effect of overstating storage effects in lighter structures and thus making the benefits of heavier structures appear to be less than they really are.

Proper modelling of the mass effect in insulated buildings must (among other things) account for the structural mass in different categories according to their respective thermal coupling characteristics.

Therefore, when a particular design is being evaluated and there is a desire to quantify the mass effect, care should be taken in the modelling of thermal coupling of the various mass components.

B.2 Mass Benefits At The Design Stage

Additional mass in heavy construction can reduce the annual heating requirements of a building. It is possible to express this mass effect in terms of an equivalent amount of insulation (R value) of a component that would result in the same saving.

The "Measures for Energy Conservation in New Buildings 1978"* (referred to as the "Measures") have given some recognition to this benefit by allowing designers and builders to reduce component R values (walls or roofs) below prescribed levels, by the amount of R value that is equivalent to the mass effect.

Designers and builders may thus choose either the immediate benefit by paying for less insulation or they may choose to meet the prescribed levels and accrue the mass benefits each year in terms of reduced heating costs.

Although the allowed R value reduction may be small in some cases, it may be just sufficient to avoid the cost of the next step in R value. This step can be considerable if a particular construction technique is approaching its limit of economical installation of additional insulation.

The Division of Building Research, National Research Council of Canada has published "Relation Between Thermal Resistance and Heat Storage in Building Enclosures" (BRN 126, revised Jan. 1979) as a guide to the quantification of R value allowance for "heavy" construction. This is a general guide that incorporates many simplifying assumptions for ease of use when complying with the "Measures".

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* Prepared for the NRCC Associate Committee on the National Building Code by its Standing Committee on Energy Conservation.

B.3 Use Of Building Research Note 126* For Compliance With The "Measures"

BRN 126 is a graphical guide to evaluating the mass effect in terms of an equivalent difference in R value (ΔR) of the component. The publication contains elaborate supporting information, worked examples and simple graphs for use in the calculation. There is one procedure for mass on the interior of the insulation layer and another for mass on the exterior. A summary of these procedures is provided herein.

B.3.1. Mass On The Interior Of The Insulation Layer

The procedure consists of 5 easy steps for evaluating the ΔR-equivalent of wall mass that is inside the insulation:

(1) Establish type of building and choose the appropriate graph (either Figure B4 or B3**).

(2) Find the building mass per unit floor area — excluding the wall mass.

(3) Find the building mass per unit floor area — including the wall mass.

(4) From the appropriate graph chosen in step (1) find the ΔR equivalent for each of the masses: step (2) and step (3).

(5) Subtract the ΔR without wall mass from the total ΔR to get the effect of the wall mass alone.

The same procedure would be followed for roof mass which is inside the insulation.

Additional Notes to Each Step

STEP (1) Buildings have either high or low energy requirements for lighting, fans, and pumps. As a general rule of thumb, large commercial and office buildings that require forced ventilation and air cooling to maintain liveable conditions, fall in the "high energy requirements" category. Smaller structures and residential buildings generally are classified as "low energy requirement" buildings.

STEP (2) & (3) A simple procedure to estimate mass per unit floor area is to add up all the mass inside the insulation of the structure and divide by the floor area.

Total mass of:
- floor slab
- + beams, columns, partitions
- + furnishings

} STEP 2

- + mass layer of the wall inside the insulation

} STEP 3

Then divide each total by the floor area.

For large buildings (office buildings, etc.) the method only accounts for the outer "ring" of building space. The floor area of this "ring" is estimated to be about 1.5 times the total exposed wall area, as a general rule of thumb. In such a case, disregard all mass in the centre core (only the mass in the outer ring counts) and divide the mass total by the effective floor area (i.e. 1 the wall area). This last procedure is required because in large buildings, the mass in the core of the building is poorly coupled with the heat loss area.

When finding the total mass of the walls, disregard mass on the exterior of the insulation for now, and note that window areas do not contribute significantly to the wall mass.

---

* "Relation Between Thermal Resistance and Heat Storage in Building Enclosures", Division of Building Research, National Research Council of Canada. Revised Jan. 1979 (BRN 126).

** The ordering of figures has been retained from the order found in BRN 126. Figures B2 and B1 are discussed below.

To be effective, mass layers must be in direct contact with interior air. This is taken to mean that no material having an R value of 0.2 or greater lies between the mass layer and the interior air. Thus the presence of interior insulation, false ceilings, sprayed asbestos fire proofing or carpeting would negate the inclusion of the mass layer to which they are applied.

STEP (4) If the starting R value corresponds to one of the lines on the graph, read off the ΔR's that correspond to the starting R value and the mass per unit floor area.

If the starting R value falls in between two lines, interpolate the ΔR results for each adjacent R value.

STEP (5) The ΔR attributable to floor mass, beams etc. must be subtracted from R-total, because the method does not allow an R reduction for these structures. This does not mean to say that this mass has no effect — it is not allowed for in the codes.

Example 1

Given: Multi-storey office building, each storey has:

— 1680 m^2 of floor area (40 m × 42 m)

— 600 m^2 of gross wall area, including

— 200 m^2 of window area

The volume of all structural and other mass inside the insulation layer are multiplied by appropriate material densities to yield the total mass of one storey:

— floor slab:	504 000 kg
— moveable partitions, and furnishings: (100 kg/m^2 of floor area is a standard allowance for these components)	168 000 kg
— total wall mass inside insulation:	100 000 kg

The minimum wall R value specified in the "Measures": 3.0 $m^2 \cdot °C/W$

Solution: Following each of the 5 steps

Step #

(1) CHOICE OF FIGURE TO BE USED
An office building of this size would have high energy requirement for fans, pumps, lighting. Use Figure B4 in the analysis.

(2) USEABLE MASS OF FLOOR SLAB, MOVEABLE PARTITIONS AND FURNISHINGS PER USEABLE FLOOR AREA
Because the building is large, only the outside "ring" of floor area is allowed in the analysis. From the formula given in BRN #126:

A "Ring" = 1.5 × GROSS WALL AREA
= 1.5 × 600 m^2
= 900 m^2 of floor area

The total mass of floor slab, moveable partitions and furnishings is calculated as

504 000 kg + 168 000 kg = 672 000 kg for 1680 m^2 of floor area

assume that this mass is evenly distributed over the floor, so that the 900 m^2 of floor area in the "ring" would have

$$\frac{672\,000 \text{ kg}}{1680 \text{ m}^2 \text{ of total floor area}} \times 900 \text{ m}^2 \text{ of "ring" area}$$

= 360 000 kg of floor slab, beams, columns, partitions and furnishings

Therefore, MASS PER UNIT FLOOR AREA:

$$\frac{360\,000\ kg}{900\ m^2} = 400\ kg/m^2$$

(3) **TOTAL** MASS INSIDE THE INSULATION LAYER PER USEABLE FLOOR AREA

Since all of the wall inside the insulation is part of the "ring" area, then all of that mass can be used in the analysis:

Total Mass = 360 000 kg + WALL MASS

= 360 000 kg + 100,000 kg

= 460 000 kg per 900 m^2

PER UNIT FLOOR AREA =

$$\frac{460\,000\ kg}{900\ m^2} = 511\ \frac{kg}{m^2}$$

(4) RESPECTIVE $\triangle R$'s

From Figure B4,

for 400 kg/m^2 and R3, $\triangle R = 0.69\ m^2 \cdot °C/W$

for 511 kg/m^2 and R3, $\triangle R = 0.82\ m^2 \cdot °C/W$

(5) $\triangle R$ DUE TO WALL MASS ALONE

$\triangle R$ due to wall mass alone is the difference between the result for the total and the result for all other mass:

$\triangle R$ wall = 0.82 - 0.69

= 0.13 $m^2 \cdot °C/W$

The allowable minimum wall R value that would also meet the "Measures" with that heavy wall construction is:

R allowable = 3.0 - 0.13

= 2.87 $m^2 \cdot °C/W$

OTHER NOTES

The identical procedure can be followed for roof mass that is on the interior of the insulation.

If both wall and roof mass are on the interior for a single storey building, the method unfortunately cannot differentiate between interior wall mass and interior roof mass. Therefore, to maintain the simplicity of the approach, one can only get an R reduction allowance for either the wall or the roof:

If the wall R reduction is chosen, include the interior roof mass with the wall mass in Step (3).

If the roof R reduction is preferred, include the interior wall mass with the roof mass in Step (3).

The allowance thus accounts for all the mass but it must all be applied in one component rather than distributed over both walls and roofs.

Residential Walls and Roofs (INTERIOR MASS)
The procedure is the same for interior mass in residential walls and roofs. In Steps (2) and (3), all of the floor area is useable in the calculation; no adjustment is needed. Figure B3 is used for Step (4).

Example 2 INTERIOR MASS ALLOWANCE IN HOUSES

Given: Single-detached residence:

— a bungalow with solid masonry walls and insulation outside the mass layer.

— 150 m^2 of floor area (10 m × 15 m)

— 120 m^2 of gross wall area including 15 m^2 of window area

— the mass of the interior furnishings partition walls, appliances, floor and roof inside the insulation: 7 500 kg

— the mass of the solid masonry wall is: 21 000 kg

— the minimum wall R value specified in the "Measures": 2.5 $m^2 \cdot °C/W$

Solution:

Step #
(1) The house has a low energy requirement for lighting fans and pumps — choose figure B3 in the analysis.

(2) Useable mass of interior furnishings, partition walls, appliances, floor and roof inside insulation per unit floor area:

$$\frac{7500\ kg}{150\ m^2} = 50\ kg/m^2 \text{ of floor area}$$

(3) Total useable interior mass including the solid masonry wall inside the insulation, per unit floor area:

$$\frac{7500\ kg + 21\ 000\ kg}{150\ m} = 190\ kg/m^2 \text{ of floor area}$$

(4) RESPECTIVE △R's

From Figure 3:

— for 50 kg/m^2 and R 2.5, △R = close to zero (there is little mass effect with light construction in such dwellings)

— for 190 kg/m^2 and R 2.5, △R = 0.06 $m^2 \cdot °C/W$ (a point half way between the R 2.0 and R 3.0 line was chosen).

(5) △R DUE TO WALL ALONE

△R WALL = 0.06 - 0. = 0.06 $m^2 \cdot °C/W$

The allowable minimum R value that would also meet the "Measures" with heavy wall construction is:

R allowable = 2.5 - 0.06

= 2.44 $m^2 \cdot °C/W$

B.3.2 Allowance For Mass On The Exterior Of The Insulation Layer

This procedure is similar to the one for interior wall mass but is even simpler: none of interior mass is involved, nor is the interior floor area. This means that the simple "mass/square metre" of the component's area can be used directly in reading the graphs. These are special graphs suited for exterior mass only.

The allowance can thus be calculated in two easy steps:

1. Establish building type and choose appropriate graph. (Either Figure B2 or B1).

2. From the mass per unit area of the component, and R value from the "Measures", read the allowable $\triangle R$ for that component.

Additional Notes

1. The same comments apply for the selection of building type as presented in the calculation for interior mass.

2. If the starting R value falls in between the R values in the graph, find the $\triangle R$ for the two adjacent R values and interpolate linearly.

Example 3 EXTERIOR MASS ALLOWANCE IN BUILDINGS

Given:

Assume the building in Example 1 also has wall mass on the outside of the insulation layer (the insulation layer is sandwiched between the interior and exterior mass). If this mass represents:

$$200\ kg/m^2 \text{ of wall surface area}$$

and the starting R value:

$$R = 3\ m^2 \cdot °C/W$$

Solution:

From Figure B2, $\triangle R = 0.046$

This allowable reduction in R value can be taken alone if no inside mass layer is present or it can be added to the inside allowance if there is an inside layer.

For our example building with both inside and outside wall mass layers:

$$\text{R-allowable} = 3.0 - 0.13 - 0.046$$

$$= 2.82\ m^2 \cdot °C/W$$

Residential Walls and Roofs (EXTERIOR MASS)

For mass on the exterior portion of walls and roofs in houses the procedure is the same. Figure B1 is used in the analysis.

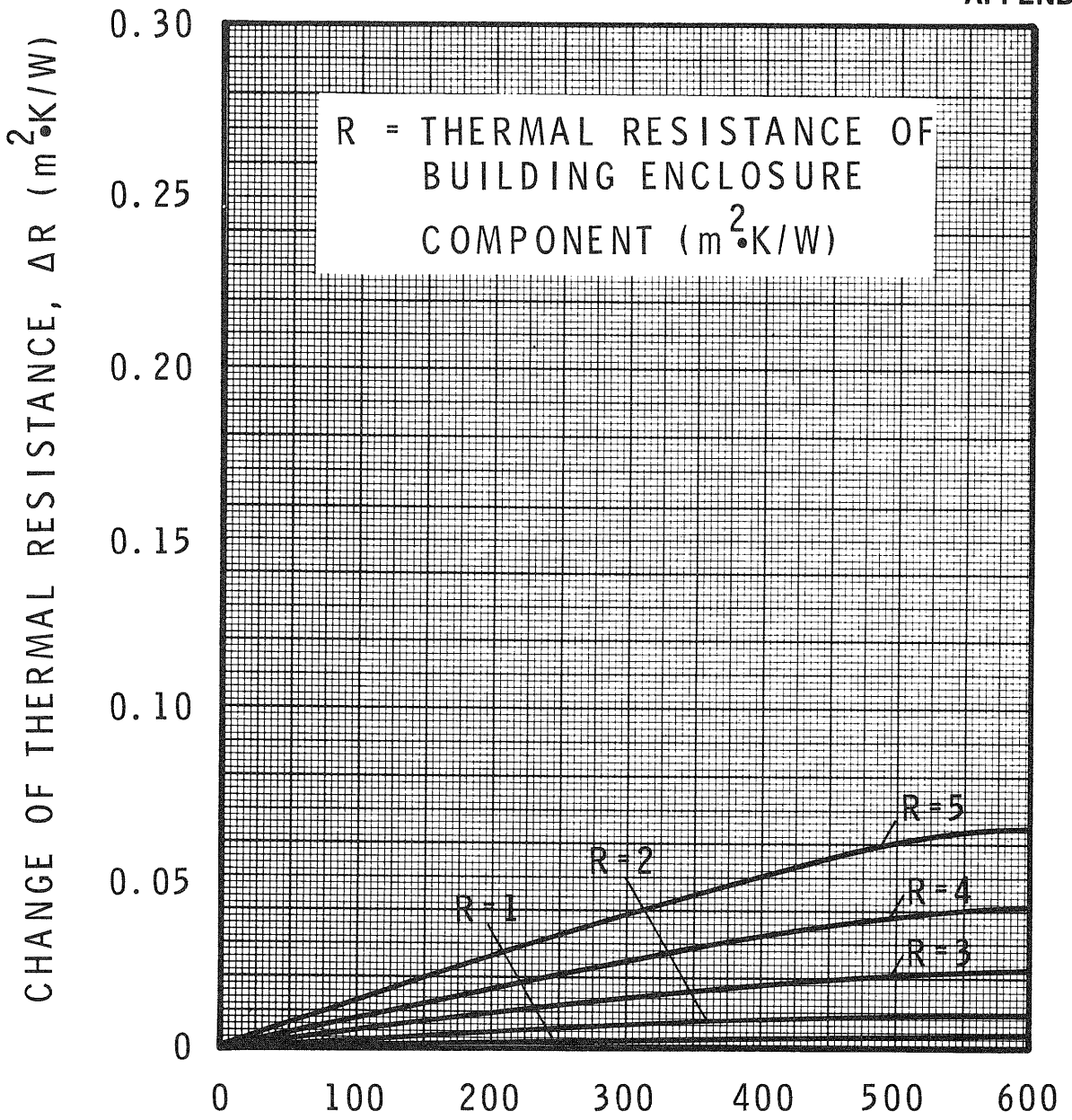


FIGURE B1

RELATION BETWEEN THERMAL RESISTANCE AND MASS OF BUILDING ENCLOSURE COMPONENT

MASS LAYER ON THE OUTSIDE OF INSULATING LAYER

TYPE OF ENCLOSURE: ENCLOSURE FOR BUILDINGS WITH LOW ENERGY REQUIREMENTS FOR LIGHTING, FANS AND PUMPS (SINGLE-FAMILY RESIDENCE)

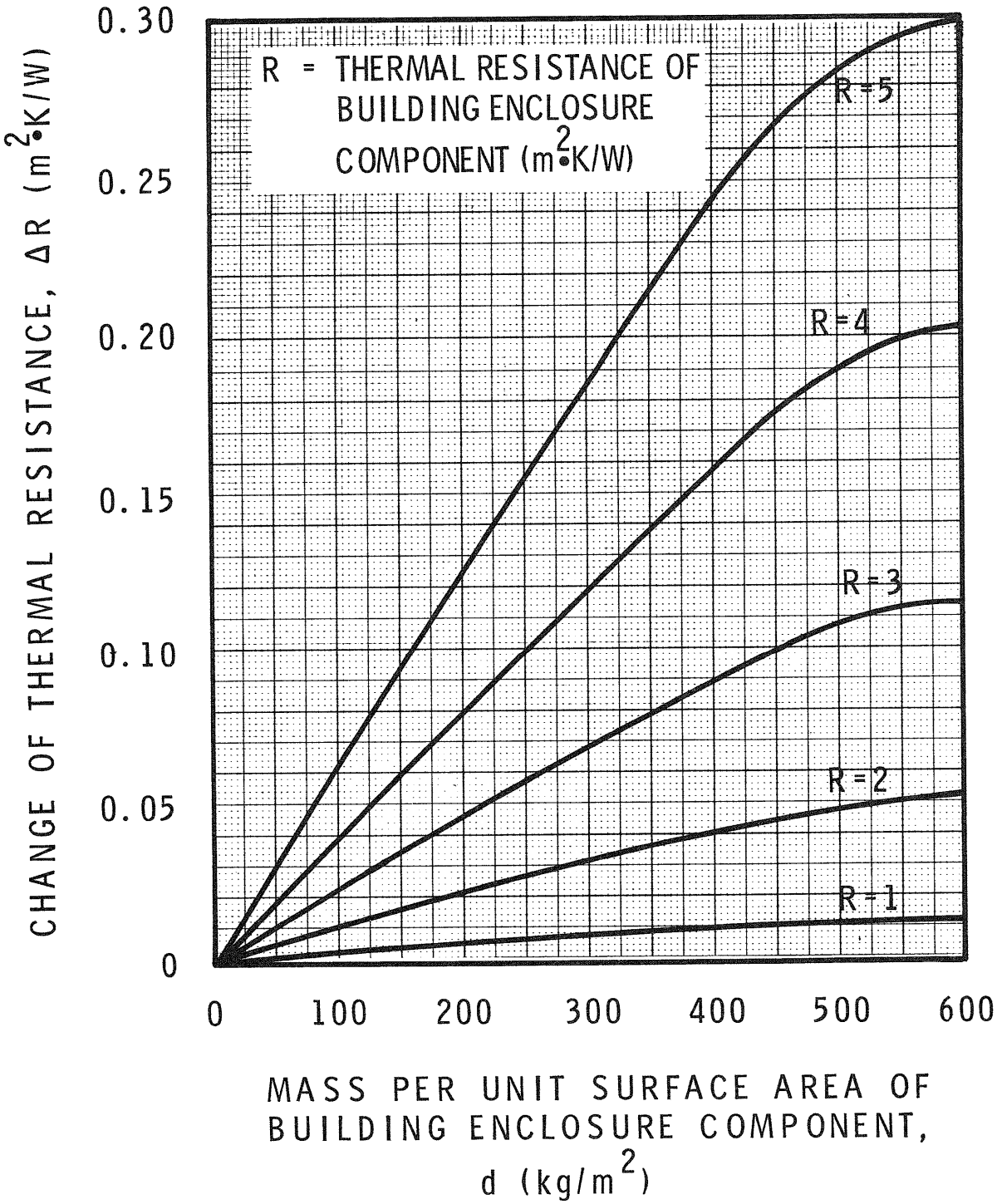


FIGURE B2

RELATION BETWEEN THERMAL RESISTANCE AND MASS OF BUILDING ENCLOSURE COMPONENT

MASS LAYER ON THE OUTSIDE OF INSULATING LAYER

TYPE OF ENCLOSURE: ENCLOSURE FOR BUILDINGS WITH HIGH ENERGY REQUIREMENTS FOR LIGHTING, FANS AND PUMPS (LARGE OFFICE BUILDING)

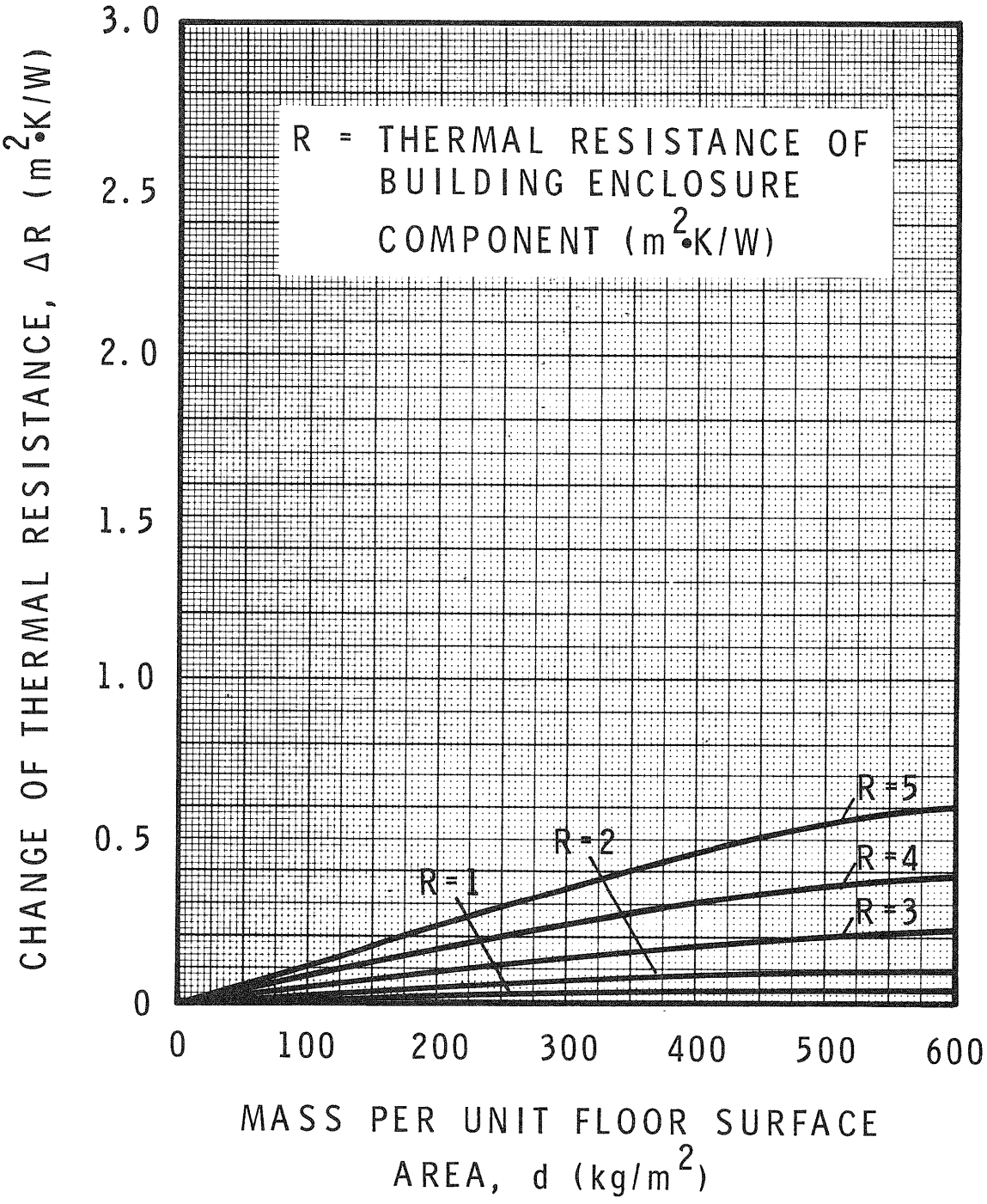


FIGURE B3

RELATION BETWEEN THERMAL RESISTANCE AND MASS OF BUILDING ENCLOSURE COMPONENT

MASS LAYER IN DIRECT CONTACT WITH INTERIOR SPACE AIR

TYPE OF ENCLOSURE: ENCLOSURE FOR BUILDINGS WITH LOW ENERGY REQUIREMENTS FOR LIGHTING, FANS AND PUMPS (SINGLE-FAMILY RESIDENCE)

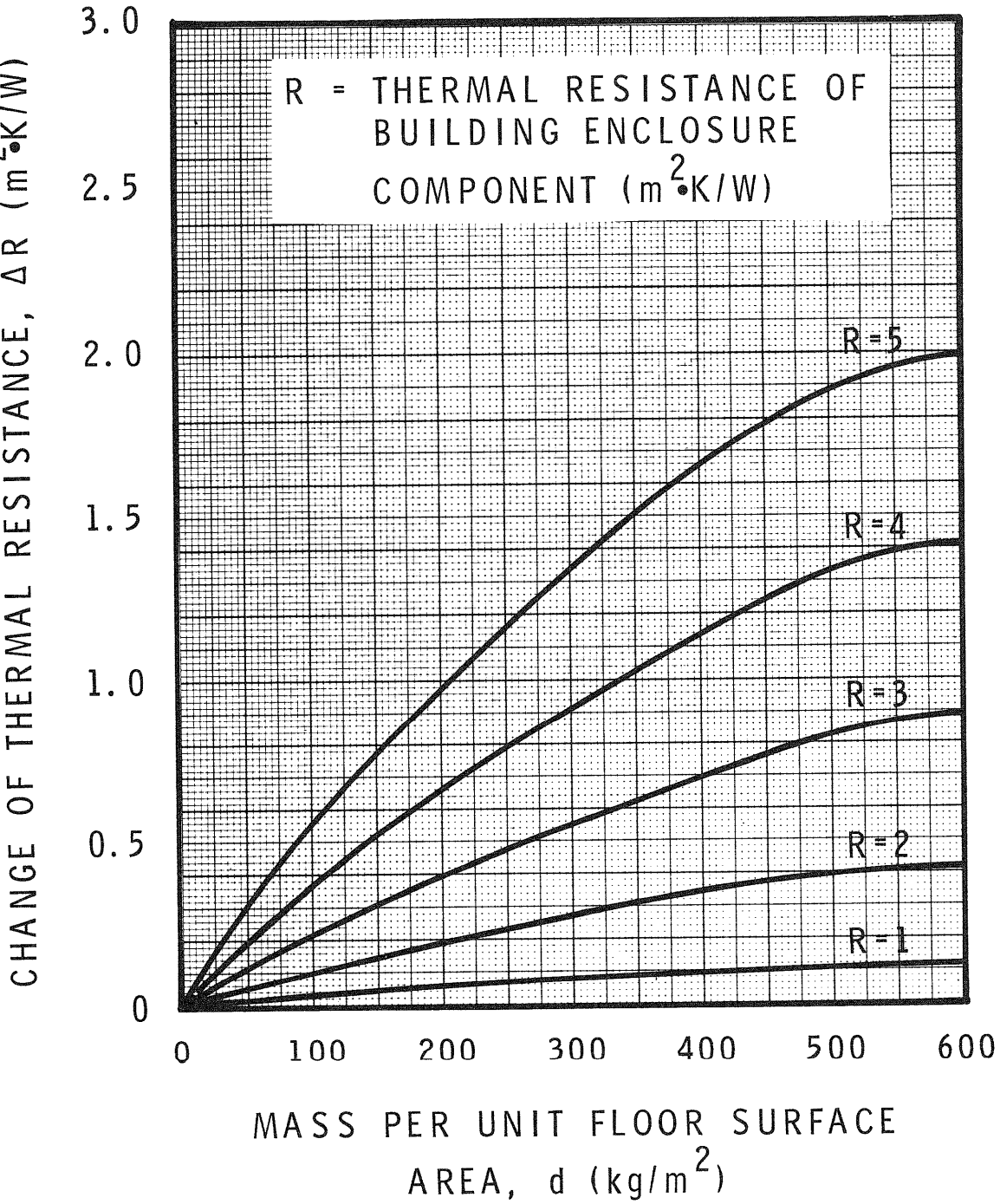


FIGURE B4

RELATION BETWEEN THERMAL RESISTANCE AND MASS OF BUILDING ENCLOSURE COMPONENT

MASS LAYER IN DIRECT CONTACT WITH INTERIOR SPACE AIR

TYPE OF ENCLOSURE: ENCLOSURE FOR BUILDINGS WITH HIGH ENERGY REQUIREMENTS FOR LIGHTING, FANS AND PUMPS (LARGE OFFICE BUILDING)

Appendix C: Window Areas And Orientation

Regulatory documents for energy conservation often include provisions limiting the maximum amount of glass area which may be provided in a building. The Measures for Energy Conservation in New Buildings, 1978*, hereafter referred to as the "Measures", contains such provision in Article 3.3.4. Article 4.3.1 requires that these window area limitations also apply to buildings with high energy requirements for lighting, fans and pumps. Article 3.3.6 makes provision for increased areas of glazing to enhance solar heating effects in winter in buildings with low energy requirements for lighting, fans and pumps, as follows:

> 3.3.6 Except as provided in Article 3.3.7, the area of glazing that contains clear glass or that has a shading coefficient of more than 0.07 that is unshaded in the winter and faces a direction within 45° of due South may be assumed to be 50 per cent of its unshaded area in calculating the maximum area of glazing in Articles 3.3.4 and 3.3.5 provided the building is designed with a system that is capable of distributing the solar heat gain from such glazed areas throughout the building. (For the purpose of determining whether or not the glazing is shaded in the winter, the shading shall be calculated using the noon sun angles of December 21.)
>
> **Note:** Article 4.3.1 excludes Article 3.3.6 for buildings governed by the provisions of Section 4.

The 50% reduction allowed by this Article for glazing oriented within 45° of South is in addition to any reduction allowed in Article 3.3.5 when glazing having a higher thermal resistance than that specified is used. This reduction applies to heat loss calculations involving the building as it is actually designed. It should not be applied in calculating the energy budget as specified in Article 3.2.4.

A design chart for determining the unshaded area of glazing for South facing glass is provided in Figure C.1. For a known sun altitude angle, overhang length and window area, the chart provides a means of determining the unshaded window area with a minimum of calculation. Design Example (a) demonstrates this procedure.

The solar noon sun altitude angle on December 21 is used to determine the effective unshaded area of glazing contributing to solar heat gains in winter. It should be noted that, for deeply inset windows not facing due South, shading by projections at the sides of the windows must be considered.

Solar noon sun altitude angles for December 21 at various latitudes are given in Table C2. Latitudes of major Canadian cities are given in Table C1.

It is stated in Article 3.3.6 that only the area of clear glass or glass with a **shading coefficient** of more than 0.70 is eligible for reduction. The shading coefficient is a factor relating the solar heat gain through a glazing system under a specific set of conditions to the solar heat gain through a reference glazing system under the same conditions. The standard reference glazing system is a single light of double strength sheet glass. Specifications for the test procedures used in determining the shading coefficient are contained in ANSI Standard 297.1-1975.

Shading coefficients for most types of glazing systems can be obtained from the manufacturer.

The Measures document also includes provisions for summer shading of glazing:

> 3.3.7 Article 3.3.6 shall not apply where the building is designed to be cooled unless the glazing described in 3.3.6 is shaded in the summer with exterior devices. (For the purpose of determining whether or not the glazing is shaded in the summer, the shading shall be calculated using the noon sun angle of June 21.)

When the building is designed to be cooled in summer, this article is used in conjunction with Article 3.3.6 in determining the area of glazing subject to the allowed 50% reduction. Any glazed area oriented within 45° of South that is unshaded in summer is not eligible for the 50% reduction. The solar noon sun altitude angle on June 21 is used to determine this area. Determination of the unshaded area may be made using the design chart in Fig. C.1. Solar noon sun altitude angles on June 21 are listed in Table C2. The provisions of this Article are illustrated in the Commentary to the "Measures" and in Design Example (b).

---

*Prepared for the NRCC Associate Committee on the National Building Code by its Standing Committee on Energy Conservation.

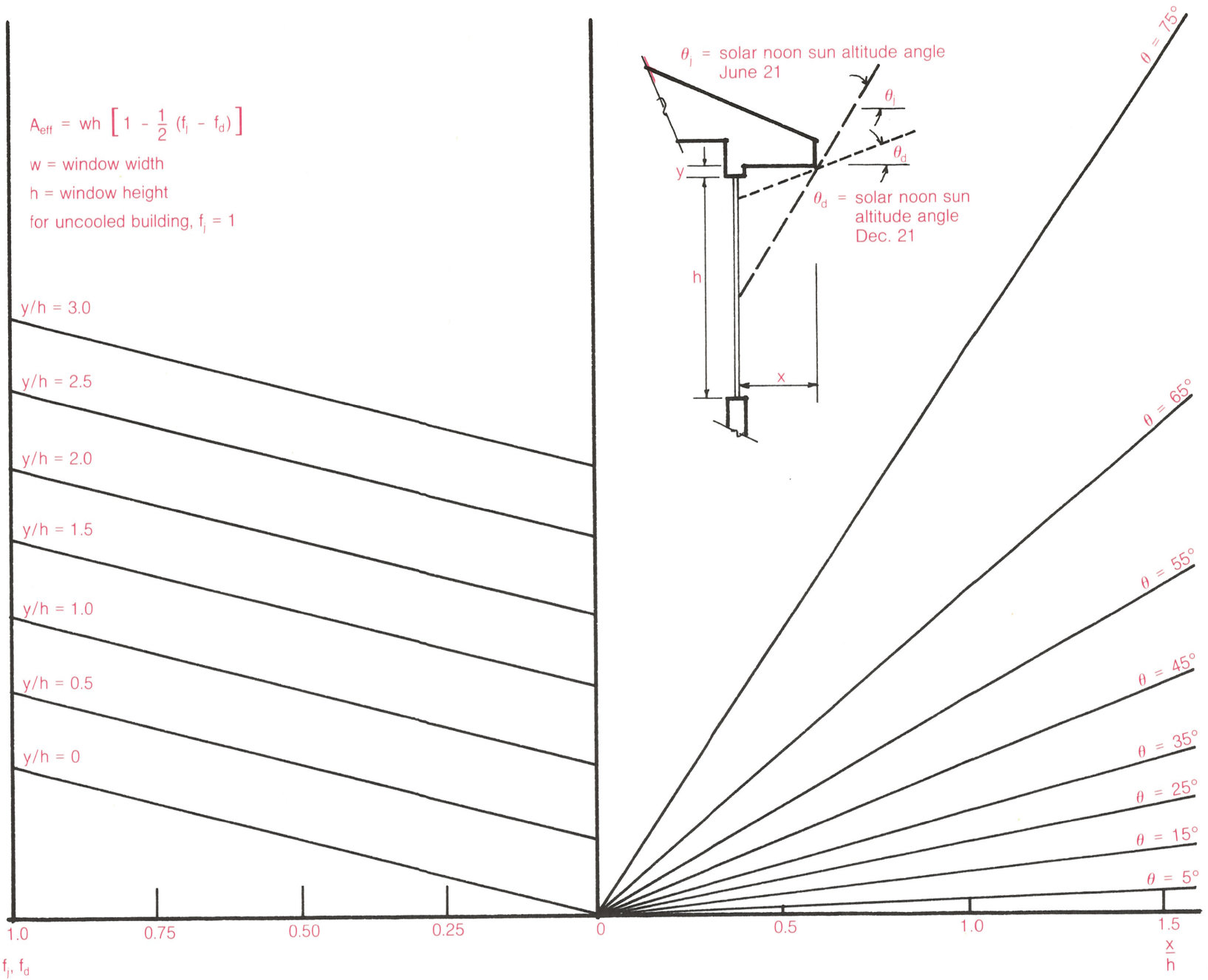


Figure C.1 Nomograph for Determining Effective Area of Glazing

Design Example (a)

The three storey apartment building shown is to be located in Toronto, Ontario (north latitude 43.7° from Table C.1 of this Appendix, 4082 heating degree days from Table A.1 of Appendix A). Overall building dimensions are 16 × 40 m. The long wall shown faces due south. Sliding glass doors are partially shaded by overhanging balconies as shown. Calculate the effective area of glazing of each sliding glass door assuming the following:

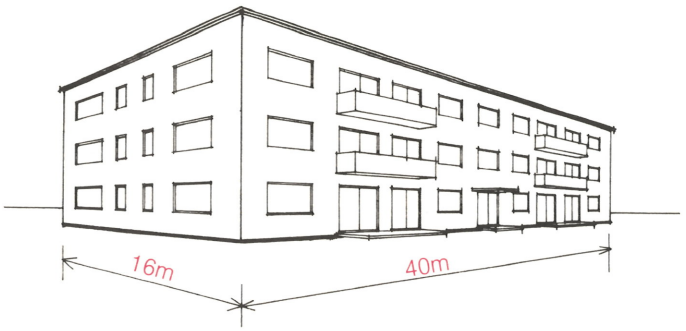
Dimensions of glazed area —

$1.98 \times 2.03 \text{ m} = 4.02 \text{ m}^2$

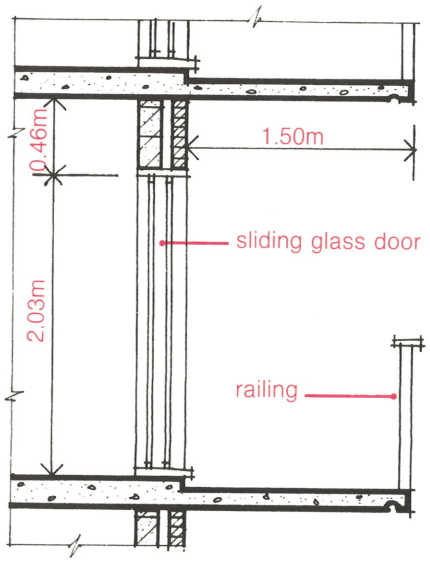
Thermal resistance (R value) —

$0.30 \text{ m}^2 \cdot °\text{C/W}$

Shading coefficient — 0.80
Building heated in winter with forced air system.
No air conditioning in summer.



Design Example — Perspective



Wall Detail at Balcony

Solution—

Since the thermal resistance of $0.30 \text{ m}^2 \cdot °\text{C/W}$ is that required by Article 3.3.1 of the "Measures", no adjustment in glazed area is allowed using the provisions of Article 3.3.5. An adjustment in glazed area is allowed by Article 3.3.6 of the "Measures" since the shading coefficient exceeds 0.7.

From Fig. 1, determine effective glazed area as follows (see Fig. C.2):

$x = 1.50 \text{ m}$ $y = 0.46 \text{ m}$ $h = 2.03 \text{ m}$

$\theta_d = 23.6 - 2\left(\frac{0.7}{2}\right) = 22.9°$ (interpolating from Table C2)

$\frac{x}{h} = \frac{1.50}{2.03} = 0.74$ $\frac{y}{h} = \frac{0.46}{2.03} = 0.23$

$f_d = 0.10$ $f_j = 1$ (uncooled building) (from Fig. C.2)

$$A_{eff} = wh\left[1 - \frac{1}{2}(f_j - f_d)\right]$$

$$A_{eff} = (1.98)(2.03)\left[1 - \frac{1}{2}(1 - 0.1)\right] = 2.21 \text{ m}^2$$

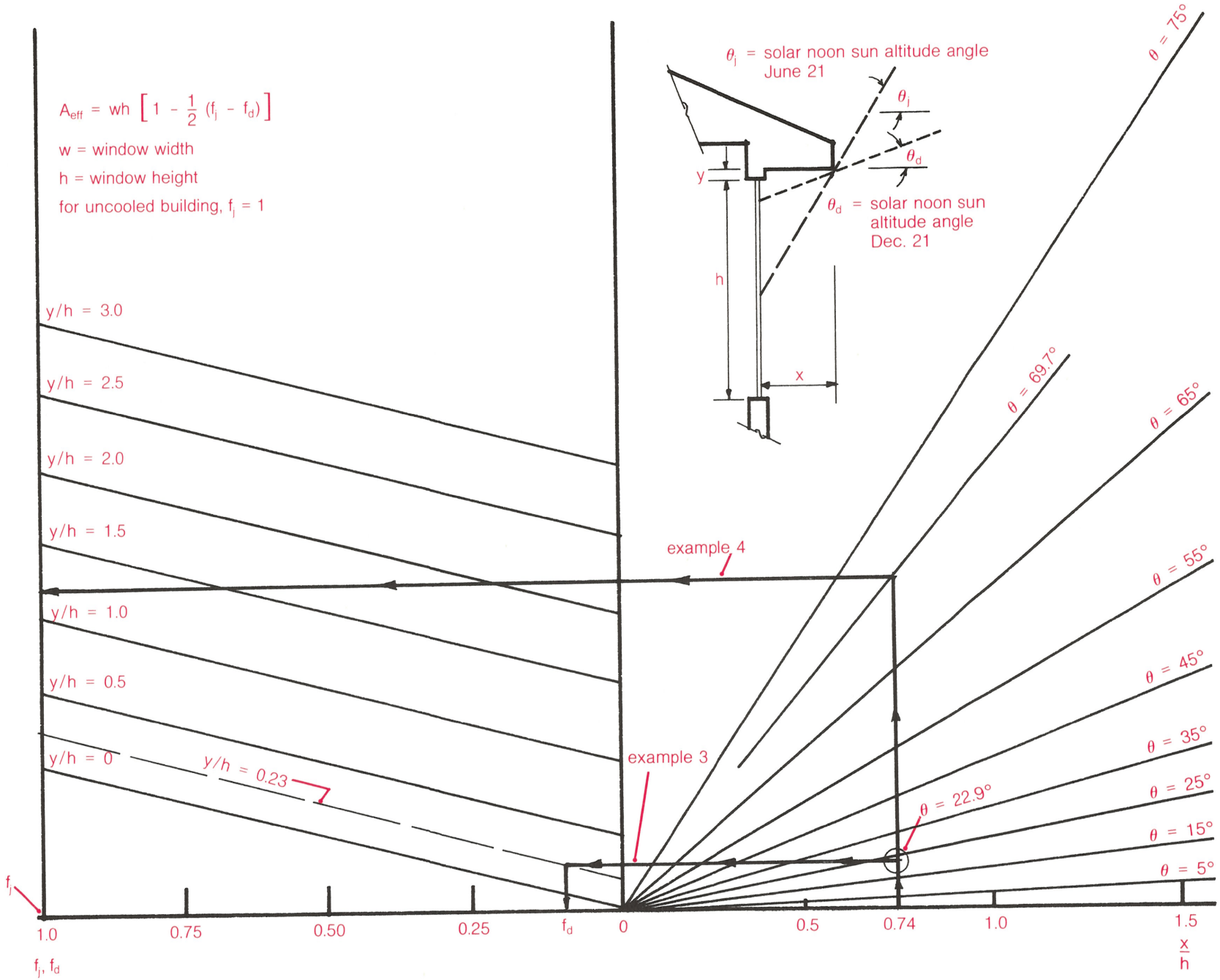


Figure C.2 Use of Nomograph for Determining Effective Area of Glazing

Design Example (b)
Calculate the effective area of glazing in Design Example (a) if the building is cooled in summer.

Solution —

$$\theta_j = 70.4 - 2\left(\frac{0.7}{2}\right) = 69.7° \quad \text{(interpolating from Table 2)}$$

From Fig. C.1 (see Fig. C.2):

$f_j = 1.0$ (means glazed area is completely shaded in summer)

$A_{eff} = 2.21\ m^2$ (same as before)

Table C1: Latitudes For Canadian Cities

CITY	LATITUDE (Degrees)
ALBERTA	
Calgary	51.5
Edmonton	53.6
Jasper	52.9
Lethbridge	49.6
McMurray	56.9
Medicine Hat	50.0
BRITISH COLUMBIA	
Fort Nelson	58.8
Prince George	53.9
Prince Rupert	54.3
Vancouver	49.2
MANITOBA	
Brandon	49.9
Churchill	58.8
Dauphin	51.1
Flin Flon	54.8
Winnipeg	49.9
NEW BRUNSWICK	
Chatham	47.0
Fredericton	45.9
Saint John	45.3
NEWFOUNDLAND	
Corner Brook	49.0
St. John's	47.6
NOVA SCOTIA	
Halifax	44.7
Truro	45.4
ONTARIO	
Hamilton	43.3
Kenora	49.8
Kingston	44.3
North Bay	46.4

CITY	LATITUDE (Degrees)
ONTARIO (continued)	
Ottawa	45.3
St. Catharines	43.2
Sault Ste. Marie	46.5
Toronto	43.7
PRINCE EDWARD ISLAND	
Charlottetown	46.3
QUEBEC	
Chicoutimi	48.4
Montreal	45.5
Quebec	46.8
Shawinigan	46.6
SASKATCHEWAN	
Estevan	49.1
North Battleford	52.8
Prince Albert	53.2
Regina	50.4
Saskatoon	52.2

Table C2: Noon Solar Altitude Angles

DEGREES NORTH LATITUDE	DEGREES NOON SOLAR ALTITUDE JUNE 21 θ_j	DEGREES NOON SOLAR ALTITUDE DECEMBER 21 θ_d
43	70.4	23.6
45	68.4	21.6
47	66.4	19.6
49	64.4	17.6
51	62.4	15.6
53	60.4	13.6
55	58.4	11.6

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